CURRENT ISSUES, ALTERNATIVE CONCEPTS, AND DESIGN CRITERIA FOR SUBWAY VENTILATION SYSTEMS

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ABSTRACT
With the growing urban population and the concern for traffic congestion and pollution (emissions control), public transportation is becoming more and more attractive to both city dwellers and managers. To gain access to the central area of the city, the subway remains the most viable alternative, despite its higher cost when compared to above ground or elevated transportation systems.

There are relatively few regulations and criteria for subway ventilation, particularly when compared with mine ventilation. The main document that provides guidance and general recommendations for subway ventilation and environmental control is the Subway Environmental Design Handbook, published in 1976 (2nd edition) by the U.S. Department of Transportation, Office of Research and Development. Many of the subway systems in existence today have been designed and built with ventilation features adequate for normal train operation, but their design does not consider stringent criteria for such emergency conditions as a train fire in a tunnel. The National Fire Protection Association's Standard for Fixed Guideway Transit Systems known as NFPA 130 as well as the ASHRAE Handbook - HVAC Applications (1995) provide specific design and operation requirements for subway ventilation systems. Some of the existing, old subways are upgrading their ventilation systems to comply with the new regulations.

The ability of a particular ventilation system design to provide adequate ventilation during normal and emergency conditions can be evaluated using computer modeling and simulation techniques. A train fire will cause a sudden change in the tunnel ventilation pattern by adding an unsteady and fast-growing source of heat. The hot air and gasses created by a fire will tend to flow uphill, possibly against the normal flow, producing a "backlayering effect." To prevent this effect from happening, enough ventilation must be provided and the governing criterion to establish the required airflow is called "Critical Velocity."

Several software packages are available for special applications on tunnel and station ventilation as well as to model the spread of smoke and heat in case of a major tunnel fire, using Computational Fluid Dynamics. This paper presents the current issues in subway ventilation, as shared by the public transit community around the world, together with modern alternative-design concepts vis-à-vis the more stringent emerging Fire-Life Safety criteria. Examples of recent studies and ventilation systems design are provided.

INTRODUCTION
The population growth in general combined with current urban development around the world and the need to move people from their homes to their places of work, shopping centers or entertainment locations in large metropolitan areas, in particular, are the principal reasons for a continuous demand for more and more transit systems.

Whatever innovations will be brought to the design and construction of mass transit systems, one thing is sure: the systems need to move more people, more rapidly, and more safely. Systems will be above ground where possible, but the competition for space, together with the need to suppress noise pollution will cause some of the new traffic to be diverted generally underground (e.g., under cities, rivers, airports, etc.).

Urbanization brings a scarcity of available land for new transportation corridors. In addition, the price of land in large metropolitan areas, coupled with the interference of new corridors with the already congested street traffic and gridlock, makes the subway transit system a viable alternative.

New subway systems are currently under construction or on the drawing boards for many large or emerging metropolises - among them: Athens (Greece), Bangkok (Thailand), Cairo (Egypt), Copenhagen (Denmark), Sao Paolo (Brazil), Taipei (Taiwan), Tel Aviv (Israel).

Existing subway systems in other large (and still growing) metropolitan areas are becoming overcrowded, and the need for extending the network as well as for increasing the speed (and consequently the ridership) is always a top priority for operators. Almost all existing subways are currently extending their systems, e.g., Hong Kong, London, Moscow, New York, Paris, San Francisco's BART, Seoul, Tokyo, Toronto.

To illustrate the order of magnitude in public transit, see the statistical data for several subway systems around the world (from Jane's Urban Transport Systems, 1991) in Table 1 on the following page.

Moscow's "Metropolitan" carries nine million persons a day, followed by Tokyo Metro with eight million, Mexico City and Paris with five million each, New York City, Hong Kong and Seoul with only 3.5 million each while London is far behind with just 2.5 million passengers every day.

For suburban mass transportation, several high speed rail projects are under construction or on the drawing board all around the world. Most of them include long tunnels and challenging ventilation systems.

Under construction is a major subway-like project in London: the Heathrow Express (HEX), between Paddington Station in London's west end and Heathrow airport, scheduled to open in 1998. This express subway line will have 8 km of new railway tunnels and two major underground stations.

Another interesting project, not a subway but requiring major ventilation capability is the Channel Tunnel Rail Link, from the Channel portal in Kent to the St. Pancras Station in downtown London.
The Storebaelt Tunnel, a rail link between London and Taegu, 16.9 and 18.3 km long, respectively, requiring high speed passenger and freight trains. The tunnels, with an internal diameter of 7.5 m, are connected by cross-passages located at these relatively short tunnels natural ventilation will be provided by openings of 25 m by 1 m, spaced evenly not more than 120 m apart [8].

**ALTERNATIVE DESIGN CONCEPTS**

### Design Criteria

In order to evaluate the effectiveness of a ventilation system, there must be a basis or criteria to check for compliance. For normal conditions, the ventilation system must maintain acceptable environmental conditions for passengers and personnel as well as suitable operation of equipment and installations. In case of fire in a tunnel or in an underground station, the emergency ventilation system must be able to control the direction of movement of hot air and smoke and the fire to enable flexibility in establishing evacuation routes and points for fire department access. Currently there are no international safety norms or standards applicable to subway ventilation systems. National standards are slowly emerging, yet there is no general consensus on their applicability. The most common practice is to have local procedures based on past experience and sometimes learn from the experiences of other agencies or operators. In the United States, the National Fire Protection Act (NFPA) has established and enforced criteria for normal and emergency fans. The vehicle air conditioning system can operate at temperatures up to 46°C (winter) and 56°C (summer) and can operate for short periods at 60°C. Other regulations include the National Electrical Code (NEC) and the National Fire Protection Association (NFPA). The NEC requires that emergency fans be designed to withstand a temperature of 60°C for a period of at least one hour. Local fan motor controllers should be separated from the fire alarm system in case of an emergency in the middle of the tunnel. This concept is widely used in Russia and Eastern Europe. Combination of station and mid-tunnel fans. This system has significant advantages compared with the others, but its main disadvantage is the higher cost. However, for new subway systems or extensions to existing systems, the additional costs for the installation of such dedicated emergency ventilation systems can be justified. Passive vents (with and without dampers). The oldest and simplest systems in subway ventilation systems are the natural ones. These are devices that can be of crucial importance in the design of a subway ventilation system. The most effective ventilation system in tunnels would be a transverse system which would allow smoke removal from the source, thus allowing the passengers to escape safely along the tunnel in both directions in case of a fire. Such a system, however, is very expensive since it involves the installation of extract ducting in the crown of the tunnel and, consequently, enlargement of the tunnel at the fire zone where the smoke is driven along the tunnel, away from fire and passengers, thus enabling them to escape into the oncoming fresh air flow, which is much less expensive [9].

Implementation of the ventilation system for new subways varies from country to country, and sometimes from city to city. In order to design a ventilation system capable of moving air in the most convenient direction to protect passengers and provide access for fire-fighters, the following concepts and design options are most common:

**Station fans.** In this concept, fans plants are attached to the station, most often at the end of the platform, or 10 to 20 m inside the tunnel. The shafts are designed to operate as blast/relief vents during normal operation (to alleviate the pressure of the incoming trains) and also as fan shafts (by closing the dampers on the relief section of the shaft). This system is popular in North America as well as for newer subways in Western Europe and Asia. There are, however, systems where fan plants are located in the station and connected to the platform through ducts, often with an initial air distribution along the entire platform. This concept is widely used in Russia and Eastern Europe. Mid-tunnel fans. This concept applies mainly where the distance between stations is long, reducing the efficiency of station fans in case of an emergency in the middle of the tunnel. This system is also common in Russian and Eastern European subways. Combination of station and mid-tunnel fans. This system has significant advantages compared with the others, but its main disadvantage is the higher cost. However, for new subway systems or extensions to existing systems, the additional costs for the installation of such dedicated emergency ventilation systems can be justified. Passive vents (with and without dampers). The oldest and simplest systems in subway ventilation systems are the natural ones. These are devices that can be of crucial importance in the design of a subway ventilation system.
tance and use in case of a fire close to the portal and when the required ventilation is downgrade, against the buoyancy of the hot air and smoke resulting in an accumulation, in this case, the fans will be controlled by the control of smoke and provide for a safe evacuation. Doors are made of collapsible metal sheet or another material that will not damage the train in case of an uncontrolled activation.

Air barriers. This is a new concept to enhance the operation of emergency ventilation and fire suppression in pre-determined locations. The devices act like air curtains in mines, except that they are deployed by a mechanism which interlocks with the emergency fans. The advantage of this operational design is that the un-deployed air barriers allow trains to pass without any restrictions or speed limitations. Still in the experimental stage, these devices have been successfully tested in the Washington subway.

Platform edge doors in stations is probably the most recent innovation in subway ventilation system design. A thin wall with doors along the entire platform isolates the tunnel from public areas. When the train arrives and stops, the platform edge doors open at the same time the train car doors open; before the train leaves the station, the doors close. The new subways in Hong Kong and Singapore are equipped with this system, which is gaining in popularity, particularly where the stations are designed with an ECS.

Other innovations in subway safety which have been tested in the Hong Kong subway consist of pedestrian cross-passages in tunnels, a hand with wire, carbon dioxide, and radio communications system linked to the center control, video equipment installed at each station and monitored from the central control room, providing vital information on emergency situations.

New subways under construction or on the drawing board provide for the installation of heat, smoke and gas sensors in order to detect a fire at an early stage and to transmit the information directly to the central control room. Some of these sensors will be monitored continuously (Los Angeles Metros). Of particular interest is the design of the ventilation system for the recently built Channel Tunnel connecting England to France, which started operation in 1994.

The Channel Tunnel, with a total length of 53 km, 36 km under sea, at an average depth of 42 m, consists of two tunnels: two running tunnels, 7.6 m in diameter, and a service tunnel, 4.8 m in diameter (in the middle), connected to the main tunnels every 375 m by cross-passages, 2 m in diameter (8). The running tunnels are also connected by 2 m diameter pressure relief ducts above the service tunnel, every 250 m. There are two crossover chambers, each 163 m long, 21 m wide and 15 m high.

Two ventilation systems have been installed, one for normal operation, and the other for emergency purposes, particularly those requiring the control of smoke [14]. The normal ventilation system supplies air to the running tunnels through air distribution units located above and below the tracks, and cross-passages by means of a ventilation plant located on each coast.

Each ventilation plant consists of two variable pitch axial fans, each capable of supplying the required air flow. One fan at each tunnel will be operational at any one time with the other on standby, available for immediate use, should a fault occur with the duty fan. For emergency and in order to control the smoke in a desired direction, two pairs of axial fans in parallel are located at coastal sites, near to each end of the tunnel. The air flow can be modified or reversed by varying the blade pitch, thus avoiding loss of control of air movement which would be caused by reversing the motor direction. Trains passing through the tunnels and their associated facilities produce both positive and dead airflow. The dead airflow will be quickly exhausted by the fans. The flow speed quickly to other tracks and a locomotive in the back of the train. The heat and smoke from the blast were so intense that only 13 minutes elapsed before the tunnel was cleared. It took eight hours to put out the fire, with eight people injured by smoke inhalation and more than 30 injured by burns.

The fire, labeled "the English Channel tunnel's worst accident" caused the closure of the Channel Tunnel for several days, the first major closure. A disastrous fire in the Baku subway, on 28 October 1995 caused the death of 289 passengers, with another 285 severely injured [218]. The fire started by a man who set himself on fire and ran around the world (including on the Internet) and labeled journalists as "the deadliest accident in the history of underground travel" (San Francisco Chronicle, October 30, 1995).

The fire at King's Cross Station of London Underground on 18 November 1987 resulted in the deaths of 31 people, including one fire-fighter. This fire accident has been the most studied and referenced tunnel fire, and its outcome is the application and acceptance of CFD modeling technique as the tool for the analysis of smoke control in case of a station fire. The fire in the San Francisco Bay Area Rapid Transit (BART) transection tube on 17 January 1979 led to the death of one fire-fighter and injury to 44 other fire-fighters. In the same year, a fire in the 2-km Nihonzaka Tunnel in Japan raged for 159 hours and destroyed 173 vehicles, causing the tunnel's closure for nine weeks.

The fire in the San Francisco Bay Area Rapid Transit (BART) tunnel was one of the largest examples of the use of numerical techniques for the design and operation of ventilation systems as a result of the fire. The fire in the tunnel killed one fire-fighter and injured 44 other fire-fighters. In the same year, a fire in the 2-km Nihonzaka Tunnel in Japan raged for 159 hours and destroyed 173 vehicles, causing the tunnel's closure for nine weeks.

Research and Development - Fire Tests

The public's increased awareness of safety issues together with an increasing density in train movements has forced subway operators to examine the options available in providing fresh air to passengers in tunnels, providing safe egress routes in case of train fires in tunnels. Several research and development programs, including real fire tests have been conducted in the United States, England, U.S. and Japan.

In the early 1990s, the Eureka 495 EUROTUN project included tunnel fire tests in an access tunnel to a copper mine in Norra Metall.

A series of tunnel fires was carried out in a gallery on the Hunsrück, a natural mountain in West Germany, using a range of fire sizes from 0.15 MW to over 4 MW and various fire dispositions. Here, tunnel fires were provided for short-term simulations with results available second-by-second or as a summary for any selected time interval. A complete combustion program was developed, analyzing the critical velocity at the fire location (based on the fire size, tunnel geometry, and grade) allows a rapid assessment of ventilation adequacy.

As a fire condition as defined for this analysis is a fully engulfed, single car fire. This condition is generally simulated during winter ambient conditions when air densities and buoyancy forces may be greatest.

The fire conditions in tunnels are generally suitable for one-dimensional analysis with software such as the SES program. This method is inappropriate, however, when the incident train is stopped at a platform or car at a station. The tests for short-term simulations with results available second-by-second or as a summary for any selected time interval. A complete combustion program was developed, analyzing the critical velocity at the fire location (based on the fire size, tunnel geometry, and grade) allows a rapid assessment of ventilation adequacy.

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Sansearch projects ARSENAL, the British Hydromechanics Research Association (BHRA) and committee organizes one or two seminars on new safety norms. Simulations, and forums on the society's winter meetings. Facilities consists of ventilation systems, but inform from simulations has to be reduced to a manageable and useable format (files that contain 50 to 100 Mbytes of data are not uncommon for a relatively small CFD application).

Smoke and temperature concentration contours can be presented in a sequence of time steps. Using computer animation, two-dimensional cross-sections can “compress” the information into an understandable form. It is possible to move the two-dimensional “slice” through the three-dimensional model and so to create a visualisation of the complete flow of smoke. ARGOS, a computer program developed by the Danish Institute of Fire Technology, is used to calculate fire, smoke, and heat development as well as evacuation times for people in the tunnel [7]. The program simulates smoke and includes optical smoke density under certain conditions. The temperature in various smoke layers as well as heat radiation from the hot smoke layer as a function of time are predicted. The program is said to be capable of producing a more realistic portrayal of the smoke patterns in the tunnel (visualisation), and to give an indication of the reduction in visibility that follows the fire outbreak. Visual assessments can be made of the safety of the proposed evacuation procedures by using the visualisation technique to view the smoke development, as predicted by a CFD model, from any angle or observation point, either moving or static, using the Silicon Graphics Explorer program.

Professional Associations and Organizations

ASHRAE's Technical Committee 5.9 Enclosed Vehicular Facilities consists of ventilation professionals from North America and some international corresponding members. The committee meets twice a year in formal meetings and is responsible for the specialized section of the society's handbook. Seminars, symposia, and forums on tunnel ventilation are organized mostly during society's winter meetings.

The American Public Transit Association (APTA) has a sub-committee on tunnel ventilation, as part of the Structures committee. Annually, during the Rapid Transit Conference, the sub-committee organizes two seminars on tunnel ventilation, open for papers from around the world.

The NPGA 130 Technical Committee is in charge of the Fixed Guideway Standard 130, providing a comprehensive review and update of this standard and making recommendations for inclusion of new safety norms.

Specialized international conferences on tunnel ventilation and other safety-related topics are organized at regular intervals by the British Hydromechanics Research Association (BHRA) and the International Technical Conferences (ITC) of the U.K. Occasional technical meetings are organized by the European research projects ARSENAL, EUTUA, CETU (France), British Rail, and Fire Research Station.

CONCLUSIONS

Significant progress has been made in the design of subway ventilation systems over the last two decades. The need for more and safer mass transit systems and the public awareness for comfort and safety require attention from operators and designers alike worldwide.

The CFD modeling technique is clearly advantageous as it provides the capability to predict fire phenomena during a fire, showing the spread of smoke and heat in all dimensions, thus enabling development of meaningful evacuation and fire-fighting plans in large and complex subsurface structures. When considering the benefits and costs associated with this relatively new tool, both designers and operators should examine not only its applicability but also the benefits and advantages over other methods.

A thorough transient simulation of a fire in a transit tunnel or station requires much modeling and computational time. In addition to establishing a representative grid of control volumes, model development requires establishing time-dependent boundary conditions and fire effects. In dealing with tunnel and station fires, the required size of the physical model to incorporate all features of interest can be very large. Such a model would be comprised of hundreds of thousands of cells and would require an enormous amount of computation time, particularly if transient conditions are simulated. There are difficulties in measurement and experimental techniques for identifying accurate velocity components. Average velocities are obtainable, but directional differences can be significant. Therefore, experimental techniques for test studies to generate data for CFD problems need to be identified. The concept that test cases are significantly simplified from real world situations is problematic.

The CFD modeling technique presents clear advantages for single-dimensional software, as it provides the capability to predict what happens during a fire, showing the spread of smoke and heat in all three dimensions, thus enabling the development of meaningful evacuation and fire-fighting plans in complex subsurface structures, as stations do. Of the parameters that describe the state of the system, temperature, mass-fraction of smoke, and air velocity are the most revealing during a tunnel or station fire analysis. Graphical presentation of the results along cross-sections through the model, shown as color coded contours or vectors, provide a more comprehensible picture than does tabular output. For transient simulations, results obtained at frequent time steps during the propagation of a fire allow for animation and provide capabilities for video presentation.

Recent progress in presenting simulation results include virtual reality which provides a means of creating computer representations simulating the real world. A virtual reality user can "walk through" the environment at will, pass through walls to see what lies behind or take a bird's-eye view of the complete field, such as in an evacuation situation.

REFERENCES


American Society of Heating and Air Conditioning Engineers (ASHRAE), 1995, "Applications Handbook"