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Fires in vehicular tunnels

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ABSTRACT: Due to improved, stringent safety regulations, many modern road tunnels are statistically safer, per kilometer, than above ground roadways. However, the public perception and reaction in the event of a serious tunnel fire is very different to that associated with a surface incident. Vehicle fires in road and rail tunnels are recognized to represent an immediate and extreme danger to the patrons of those systems. Unlike workers in the mining and civil construction industries, the general public are neither trained nor equipped to fight fires or evacuate under deteriorating smoke conditions. Accordingly, for the majority of modern transportation tunnels the ventilation infrastructure is sized on the requirement to control the combustion products from worst-case fire scenarios and to provide a tenable evacuation route for the tunnel users. It is common for these same emergency ventilation systems to be employed, often in a reduced capacity, for other operating modes such as the dilution of pollutants during congested traffic conditions. This is one of the fundamental differences to mine ventilation, where primary ventilation systems are not typically sized based on fire scenarios. This paper presents an overview of the subject of fires in vehicular tunnels. This includes a brief history of major transportation tunnel fires followed by a discussion on the resulting legislation and standards that govern the design and operation of tunnel emergency ventilation systems. A summary is provided on the common criteria, theory, and design techniques that are employed during tunnel emergency ventilation systems design. Information is provided on fire detection and suppression, with a discussion on the growing acceptance of wet suppression as a means to mitigate major fires in road tunnels worldwide.

1 Introduction

Worldwide there are many thousands of road and rail tunnels used by hundreds of millions of people on a daily basis. Some of these tunnels are relatively modern, incorporating the latest engineering design standards and innovations in ventilation fans, dampers and associated equipment and infrastructure. However, the majority of tunnels in service are old and in many cases they do not meet the required safety standards of modern tunnel systems.

Road and rail tunnels represent different but equally important challenges in terms of fire-life safety. Subway systems are typically complex networks of tunnels and stations, located in heavily urbanized areas. The tunnels are, in many cases deep, with little room for emergency ventilation shafts and fan rooms. The New York City subway system is one such example, consisting of over 1,000 km of revenue track and 468 stations, with approximately 60% underground. Yet, not all stations and tunnel sections are provided with adequate ventilation systems. The week day daily ridership on this system exceeds 4.8 million passengers. Risk based studies have, or are being conducted on these older transit systems to identify where the high risk areas are, and what upgrades should be planned to provide an acceptable level of safety for patrons.

The series of catastrophic (in terms of loss of life and high cost) road tunnel fires in Europe resulted in the spotlight being focused on road tunnel safety since 1999. The European Union has been proactive in developing a directive for upgrading existing road tunnels to ensure that the emergency ventilation and evacuation facilities are correct for the type of tunnel (considering issues such as length, whether bi-directional traffic is allowed, the peak fire load of the allowed vehicles, the gradient and geometry of the tunnel, whether there are adjacent tunnels, as well as the speed and capability of incident response).

2 Overview of Tunnel Fires

Fires within tunnels and other underground structures represent an immediate and extreme danger to the life of the patrons using the facility. It is the responsibility of the operator to ensure that the safety systems and procedures are adequate to cope with the case of a major fire. Depending on factors such as the geometry of the tunnel, slope, availability of a ventilation system and the source of the fire, smoke movement along tunnels can be significantly faster than the walking speed of passengers attempting to escape. In many cases, particularly in road tunnels without mechanical ventilation, the hot buoyant smoke may remain stratified against the roof of the tunnel for a significant period, allowing egress beneath. At some point however this smoke will cool and drop back down. In other cases, particularly when the longitudinal air velocity is high along the tunnel, the smoke will be immediately mixed within the airstream, effectively filling the entire tunnel downstream of the fire.

Figure 1 is a photograph of an actual road tunnel fire. It is obvious, given the fire and rapidly developing smoke layer, that the motorists need to make decisions quickly and accurately. It is interesting to note that many frequent users of road and rail tunnels do not give thought to how they should react in the event that they (and their families) encounter such a situation. Many of the longer European road tunnels, such as Mont Blanc, provide cards with critical safety information, which is similar in concept to a safety orientation conducted at any mine. The cards provide details on action to be taken, location of refuge and escapeways, methods of communication, etc.

The design of emergency systems for vehicular road and rail tunnels represents a unique challenge and responsibility for engineers. The design processes for these systems are very different than those used for mines, with particular attention paid to fire analysis, emergency egress, and code compliance. Emergency ventilation systems are designed to protect the general public who patronize the facilities, for they are typically untrained, unpredictable, and carry no personal protective equipment. There is reliance on the design of the system, coupled with assistance from facility personnel. The engineer acts not only as the designer, but also as a guardian of the pubic trust, with a responsibility to insure that the fire-life safety considerations of the system are properly addressed.

In the case of a fire, well designed, maintained and operated ventilation and fire suppression systems are vital to ensure that egress routes are kept clear for long enough to allow tunnel users and employees to escape safely. If properly designed and operated, the tunnel ventilation system should also be capable of maintaining at least one egress path clear indefinitely, guaranteeing an escape route as well as access for emergency response personnel.

2.1 Brief History of Road Tunnel Fires

Road tunnel fires typically result from electrical fault, brake overheating or other mechanical causes. In the majority of cases these are small fires that are rapidly extinguished, either by motorists or emergency responders. Other less frequent (but potentially more severe) reasons include collisions and maintenance work in the tunnels. In general it is noted that trucks have a higher frequency of fire than passenger cars, and that the risk of vehicle fire increases when the grades are steeper or bends are introduced.

In particular, older trans-Alpine road tunnels have been the focus of recent studies and ventilation system upgrades and improvement. Disastrous fires such as those occurring at the Mont Blanc (39 fatalities), Tauern (12 fatalities) and Gotthard (11 fatalities) tunnels have resulted in tunnel operators reconsidering the suitability of existing ventilation systems, particularly in bi-directional, longer facilities. Table 1 provides a list of some of the main road tunnel fires over the last 30 years in which there have been one or more fatalities. It is noted that in many cases the cause of the fatality was associated with collision and not necessary with hazards from the ensuing fire.

The Mont Blanc Tunnel is one of the major trans-Alpine road tunnels which predominantly services Italy. The tunnel is 11.6 kilometers long, 8.6 meters wide, 4.35 meters high and forms a slightly inverted "V" in longitudinal profile. The tunnel consists of a single cross section with a two-lane dual-direction roadway. The tunnel is managed by two public companies (French and Italian), each managing approximately half of the tunnel length. The 1999 fire was initiated by a truck carrying flour and margarine which caught on fire in the tunnel. Due to the inability of the firefighters to access the scene, the fire burned for approximately 56 hours, reached temperatures of +1,000 °C, and spread to other cargo vehicles nearby that also carried combustible loads (eventually trapping and burning about 40 vehicles). Some of the consequences of this fire are shown in Figure 2.

The Caldecott Tunnel fire is considered to be the worst road tunnel fire in the United States. This fire killed seven people in the north tube of the Caldecott Tunnel between Oakland and Orinda (San Francisco Bay Area), occurring just after midnight on April 7, 1982. It is one of the few major tunnel fires involving a cargo normally considered to be highly flammable, namely gasoline.

During 1982 there was a catastrophic fire in the Salang Tunnel. Few facts are known or have been published about this fire, which occurred on November 3, in Afghanistan’s only road tunnel. The fire, occurring during the Soviet-Afghan War, was apparently caused from a collision resulting in a tanker truck igniting within the tunnel. The size of the fire, duration and number of vehicles involved are unknown. This incident is regarded as one of the worst fire disasters in modern times with the number of reported casualties varying from 150 to as high as 2,000.

Figure 1. The reality of a road tunnel fire.

Figure 2. Aftermath of the 1999 Mont Blanc tunnel fire.

2.2 Brief History of Rail Tunnel Fires

Transit tunnel fires, although less common than those associated with road tunnels, have the potential to be more deadly due to the dense grouping of people. Table 2 provides a list of the some of the major fires in rail tunnels over the past 30 years.

Noteworthy is the Taegu subway fire that occurred February 18, 2003. This fire was initiated by an arsonist setting fire to one train with gasoline. The fire quickly spread to ultimately destroy two trains and cause many additional casualties at Jungangno Station. The duration of the fire was about three hours, with 192 fatalities. The Baku Metro fire, occurring October 28, 1995, was even more catastrophic and represents the worst subway fire. The fire, caused by electrical fault, broke out on an evening rush hour train. Deadly fumes of carbon monoxide from the burning synthetic materials in the cars overpowered the passengers rapidly, resulting in over 289 people killed. These fires, as well as those in North America (San Francisco BART, Toronto, and Montreal) and the infamous King's Cross fire in London have caused subsequent changes to the components of transit vehicles. These changes ensure that the vehicles are more fire hardened, the smoke is less toxic, and ultimately help prevent disasters of this magnitude from occurring in the future.

Table 1. Selected road tunnel fires during the last 30 years.

Date	Name	Country	Length	Cause of Fire	Fire Duration	Fatalities/Injuries
Mar 2007	Burnley Tunnel	Australia	3,400m	Truck / car collision	1 hr	3 dead / 2 injuries
Sep 2006	Viamala A-13	Switzerland	742m	Car & bus collision	4 hrs	6 dead / 6 injured
Jun 2005	Fréjus T2	France-Italy	12,895m	Truck fire – mechanical	6 hrs	2 dead / 21 injured
Oct 2001	St. Gotthard A-2	Switzerland	16,918m	2 truck collision	48 hrs	11 dead
Aug 2001	Gleinalm A-9	Austria	8,320m	2 car collision	-	5 dead / 4 injured
May 1999	Tauern A-10	Austria	6,401m	2 trucks/4 cars collision	16 hrs	12 dead / 49 injured
Mar 1999	Mont Blanc	France-Italy	11,600m	Truck fire – mechanical	56 hrs	39 dead
Mar 1996	Is. De. Femmine	Italy	148m	Tanker & bus collision	-	5 dead / 20 injured
Apr 1995	Pfänder	Austria	6,719m	Car/truck/van collision	1 hr	3 dead / 4 injured
1994	Huguenot	South Africa	3,914m	Bus electrical	1 hr	1 dead / 28 injured
1993	Serra Ripoli	Italy	442m	Truck & car collision	2 hrs	4 dead / 4 injured
1987	Gumefens	Switzerland	343m	Truck & van collision	2 hr	2 dead
1986	L'Arme	France	1,105m	Truck mechanical	-	3 dead / 5 injured
1983	Pecorila Galleria	Italy	662m	Truck & car collision	-	9 dead / 22 injured
1982	Salang	Afghanistan	2700m	Military column collision	-	>150 dead
1982	Caldecott, Oakland	United States	1,028m	Tanker/bus/car collision	3 hrs	7 dead / 2 injured
1980	Kajiwara	Japan	740m	Truck collision	-	1 dead
1979	Nihonzaka	Japan	2045m	4 Truck/2 car collision	6.5 days	7 dead / 2 injured
1978	Velsen	Netherlands	770m	2 trucks/4 car collision	1 hr	5 dead / 5 injured

Table 2. Selected rail tunnel fires during the last 30 years.

Date	Name	Country	Cause of Fire	Fatalities/Injuries
Feb 2003	Taegu Subway	Korea	Arson. 2 cars engulfed.	192 dead / 148 injured
Nov 2000	Kaprun	Austria	Cable car fire from heater system. Steeply inclined tunnel.	155 dead
May 1999	Salerno	Italy	Arson suspected. Tunnel may not have been a factor.	4 dead / 9 injured
Oct 1995	Baku Metro	Azerbaijan	Electrical fault on train.	289 dead / 265 injured
1987	Kings Cross	England	Escalator fire	31 dead
1984	San Benedetto	Italy	Bomb detonated in 18.5 km tunnel. 2 cars destroyed. Small fire.	17 dead / 120 injured
1981	Moscow	Russia	Electrical fault / 2 cars on fire	7 dead
1980	LUL	London, England	Trash fire in cross-passage	1 dead
1979	BART	San Francisco, US	Electrical short-circuit	1 dead / 58 injured

3 Considerations for Designers

3.1 Legislation and Standards

Throughout the world new road and rail tunnels are continuously being built, and the mechanical systems in older tunnels are replaced, modernized, or upgraded periodically. For tunnel ventilation systems increasingly stringent standards are often applied in advance of when mechanical inefficiency or poor availability necessitates replacement. In the United States there are two main safety standards directly applicable to rail and road tunnel systems. These are National Fire Protection Association (NFPA) 130 Standard for Fixed Guideway and Passenger Rail Tunnels and NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways. These standards are developed and updated periodically through a consensus process which brings together industry volunteers representing varied viewpoints and interests. The resulting standards are broadly applied worldwide during subsurface transportation systems design, and are a requirement for most projects in North America.

There are no international standards. For road tunnels the World Road Association (PIARC) has issued guidelines that are continually revised and updated. The European Union Directive #54/EC adopted by EC Parliament in April 2004 aims at ensuring a minimum level of safety for road users in tunnels by prevention of critical events that may endanger human life. It is applicable to all existing and proposed tunnels in the Trans-European road network that are greater than 500 m in length. Other national guidelines and standards exist on a country-by-country basis.

3.2 Performance vs. Prescriptive Design

In the tunnel ventilation field designs may be broadly classified as either prescriptive or performance-based. In North America, prescriptive design has overwhelmingly been the method that engineers were required to adopt. More lately however, operators and designers are turning to performance-based design in an attempt to ensure adequate safety, while being provided more latitude to overcome challenges within the confines of budget and schedule.

Prescriptive design deals with the strict interpretation of design criteria or standards. NFPA standards have traditionally supported this approach. They provide detailed criteria on a wide variety of attributes associated with an environment during a fire. From a prescriptive viewpoint, detailed minimum standards and criteria are given in order to maintain a safe system. Examples include:

- For underground subway/metro stations there shall be sufficient egress capacity to evacuate the platform occupant load in 4 minutes or less.
- The station shall be designed to allow evacuation of all occupants to a point of safety in 6 minutes or less. Typically the point of safety denotes exiting at grade, however interior assembly points can be designated as a point of safety if it can be demonstrated that they can be maintained clear of smoke indefinitely.
- Personnel should not be exposed to air temperatures that exceed 60°C during emergencies.
- Personnel should not be required to walk into an airstream exceeding 11 m/s during an emergency.
- The minimum air velocity within a tunnel section experiencing a fire should be sufficient as to prevent back-layering of smoke. This requires understanding and application of the '*critical velocity*' concept.
- Fans and dampers shall be certified capable of operating at a temperature of 250 °C for a period of at least one hour.

Performance-based design utilizes engineering tools to demonstrate that an adopted design approach is safe and effective, even if it does not necessarily meet some of the more typical prescriptive design elements. The advent of tools such as Computational Fluid Dynamics (CFD) allowing advanced three-dimensional modeling of a fire scenario helps make this possible. CFD can be used to develop a transient model which considers a particular scenario over time. This software can be coupled with evacuation modeling software to truly model the movement of people through a potentially deteriorating environment during a fire. Performance-based design recognizes that it is not necessary to maintain an environment free of smoke and heat indefinitely, only long enough to safely evacuate patrons. Also, areas do not have to be entirely devoid of smoke, as long as people can still see and breathe sufficiently. Among designers, it is gaining acceptance, primarily because it is subjective, and allows a certain amount of flexibility and creativity when considering design alternatives that might otherwise be precluded.

3.3 Tunnel Safety Systems

Broadly the role of safety systems in tunnel facilities is to protect occupants, allow and facilitate emergency response and to limit damage to the property. More specifically tunnel safety systems comprise:

- Facilities and operations to detect, recognize and correspond in case of fire, including fire and smoke detection systems.
- Ventilation system operation in emergency mode.
- Traffic operation and information provision at occurrence of disaster, including monitoring and automatic tracking systems, and additional safety equipment (CCTV, radio, phones, signal lights).
- Escape facilities and evacuation guidance, including evacuation means and procedures.
- Fire fighting, including fire suppression, rescue equipment and procedures.
- Other important systems including electric power supply, emergency lighting system, tunnel management system, as well as shelters and dedicated evacuation routes.

Emergency Ventilation Systems: The objective of a permanent tunnel ventilation system is to insure a safe and comfortable environment under all reasonably anticipated operating conditions for patrons and employees. This covers all operating modes, namely normal, congested, emergency (fire) and maintenance.

The ventilation of tunnels may be broadly classified as natural, vehicle-induced, or mechanical. Natural ventilation relies on the pressure difference between the tunnel portals and shafts created by changes in elevation, air temperature, and wind. Vehicle induced airflows, also known as the "piston effect" can be significant. Typically during normal operating conditions, most unidirectional road and rail tunnels are self-ventilating due to the piston effect.

Mechanical ventilation systems consist of various fan/duct configurations depending on the site specific needs of the tunnel. Generally mechanical ventilation systems are required to ensure adequate smoke control during fires in subsurface facilities. Fan type and installation are varied. Most subway/metro systems in densely populated areas suffer from a lack of space for fan rooms and shafts, both below and above grade. Typically multiple reversible axial fans are used to effectively zone the tunnels and stations, allowing for longitudinal ventilation in either direction through the different sections. The efficiency of fully reversible fans is poor, especially in the confined installations common in transit systems. Fortunately the operation of these fans is generally limited to emergency mode, testing and infrequent application during congested train conditions in the summer.

Large centrifugal fans, similar to those used in the mining industry, are more common for road tunnels and non-electric train tunnels, where fan reversibility is not required. In these cases control of pollutants is required on a full time basis. A separate mode is typically employed for smoke control.

Fire Resistance and Suppression: It is important that tunnel safety systems and structures be designed to operate in the extremes of a subsurface fire event. The most reliable method for testing these safety systems is to conduct full-scale tests and expose the systems to a real event. Facilities do exist to conduct full scale tests, such as the Runehamar Test Tunnel in Norway, however, due primarily to expense fire simulation using computers coupled with component fire tests is more typically used.

Passive fire resistance is sometimes used in tunnels to help prevent severe damage to the structure in the event of a major tunnel fire. The materials may be panels formed within concrete to protect structural steel members, fibers embedded within the concrete or may be surface mounted tiles or sprayed insulation. One major consideration when insulating tunnels is that the heat from a fire will be transferred further along the tunnel rather than being absorbed by the surrounding heat sink. This will impact the operation and fire rating requirements for downstream mechanical systems such as jet fans.

Fire suppression in tunnels may consist of one or more of the following:

- Sprinklers: Wet or dry.
- Standpipe: Wet or dry.
- Hydrants: Located at regular intervals.
- Deluge systems: Open nozzles for dispersion over a set area (used in some transit stations to extinguish train fires); foam can be added for improved suppression.
- Water curtain/screen: Limited capacity to block longitudinal smoke spread, but considered efficient at blocking flame spread and shielding thermal radiation. Can be used to compartmentalize a fire within a zone (as used in Japan), sometimes with specialized nozzles (~20% water droplet diameter compared to sprinklers). Used in conjunction with water sprays.
- Water mist: Low or high pressure, with a water droplet diameter ~10% of sprinklers.

Tunnel fire tests conducted in Europe with water mist suggest a reduction of 40-70% in heat for a 10 to 22 MW fire size range, but not much impact for fires smaller than 5 MW. It was found out that the effect of water mist spray is strongly dependent upon type and location of nozzle and water discharge rate. The tests were targeted to maximize the cooling effect due to the high rate of water evaporation. A rapid reduction in downstream temperature was noted, while the smoke backlayering effect was reduced significantly due to the cooling effect of the mist. On the other hand, the visibility near fire was reduced significantly due to increased steam generation.

Water sprays are considered advantageous in preventing the fire expansion due to their cooling effect. The main benefits are:

- Protect tunnel structure and its facilities.
- Reduce the risk of fire migrating to nearby vehicles or structures.
- Cool down and help suppress the fire.
- Enhance fire-fighting and suppression.

Other Safety Systems: To protect non-incident vehicles, tunnel/station structure and equipment/facilities during a fire it is critical to determine the fire location as soon as possible. Detection options include manual recognition and identification, opacimeters, linear temperature detector, air sampling systems, digital image processing for fire/smoke detection (usually on video-cameras) and infra-red and ultra violet heat detection. Heat detection may be electronic (spot), sprinkler (fixed temperature) and linear detection (cable, fiber optic, sensors).

Evacuation consists of establishing and maintaining integrated emergency egress routes. These routes may include emergency walkways and stairs, separate tunnel/plenum/adit, refuge bays and cross passages, as well as specific marking of emergency egress routes, emergency lighting and a backup electric power supply.

3.4 Concept of Tenability

Underground fires produce elevated temperatures, heat radiation, elevated levels of toxic and and/or corrosive gases, reduced visibility and low oxygen. Visibility, heat and toxicity are the three main considerations when determining the threat associated with a tunnel fire event. These tenability criteria enable test data and simulation results to be examined to determine whether smoke and fire management systems and the response are adequate.

In general, visibility is deemed as the most stringent criterion. The human body can withstand relatively high temperatures and fire gas inhalation for short duration without severe permanent physical damage. Dense smoke, however, can cause spatial and directional disorientation and choking, resulting in delay and susceptibility to being overcome by toxic gas or heat. The situation is complicated by panic, with numerous tripping and falling hazards associated with underground facilities.

Visibility is determined from the extinction coefficient and is typically expressed as the distances that both reflective and illuminated signs can be seen through smoke. Commonly applied criteria for NFPA are that a tenable evacuation route requires that visibility is sufficient to discern an internally lit sign at 30 m and doors and walls at 10 m. PIARC states that reflective signs must be visible at 15 m. It was reported after the Taegu subway fire in South Korea (192 fatalities) that people were unable to find their way to the stairwells and escape to safety because of thick black smoke. The severity of the smoke is apparent from Figure 3, with the conditions below ground being extreme.


Figure 3. Actual Smoke from the Taegu Subway fire.

Radiant heat is produced by the fire itself and the hot smoke layer. Codes typically provide tables of maximum exposure times against temperature. A commonly applied guide for tenability is a maximum temperature of 50 °C for 18.8 minutes (NFPA). PIARC provides a limiting value of 80 °C for 15 minutes and a threshold value of 2-2.5 kW/m^2 for the radiation level.

Toxicity is dependent upon the constituent gases which may be additive, act singly or even antagonistically. Relationships exist to determine the lethality associated with gas combinations, which can be estimated from the fire constituents and previous fire testing. A simpler approach, that is often adopted, is to consider the maximum concentrations of key gases for a fire and compare against lethal thresholds (ensuring that the worst-case is met).

Transient fire simulation is often conducted to determine tenability of passenger and worker evacuation routes against time. Evacuation modeling can be coupled to obtain a true picture of exposure. At a minimum the emergency systems need to be capable of maintaining at least one tenable evacuation route from the site of the fire to a point of safety through the period of time that it takes to evacuate the facility.

3.5 Fire Heat Release Rate

Emergency ventilation systems for transportation tunnels are typically sized based on the results from simulation of fire scenarios. The scenarios examine worst-case conditions in terms of slope, proximity to leakage paths (portals, cross passageways, stations, etc.), presence of other vehicles, and design fire size. This last factor is an ongoing subject of discussion and debate in the transportation fire-life safety community. Typical peak fire heat release rates for a range of vehicular types are provided in Table 3 (after NFPA 502).

Type of Vehicle	Peak Fire Heat Release Rate (MW)
Passenger Car	5-10
Multiple Passenger Cars (2-4)	10-20
Light Rail Vehicle	9-17
Large Passenger Rail Car	20-30
Bus	20-30
Heavy Goods Truck	70-200
Diesel Locomotive	100+
Gasoline Tanker	200-300

Table 3. Typical fire heat release rates for tunnel vehicles.

When considering design fire size, the following notes are provided by NFPA:

- The designer should consider the rate of fire development (peak heat release rates may be reached within 10 minutes), the number of vehicles that could be initially involved, and the potential for the fire to spread from one vehicle to another.
- Temperatures directly above the fire can be expected to be as high as 1000°C to 1400°C.
- The heat release rate may be greater than those in Table 3 if more than one vehicle is involved.
- In the case of flammable and combustible liquids spilling from a tanker fire, the design should include adequate drainage to limit the area and duration of the pool fire.

3.6 Common Theory

It is beyond the intent of this publication to detail theory associated with tunnel ventilation design. Some of the key concepts are discussed below.

Critical velocity: This is a cardinal standard by which most transit and road tunnel ventilation systems are designed and evaluated. Critical velocity represents the minimum air velocity approaching a fully developed fire to prevent the backlayering of hot gases and smoke. Backlayering is defined as the flow of hot smoke and gases contrary to the direction of ventilation. In a tunnel, subway, or road tunnel fire scenario, this is undesirable. The Subway Environmental Design Handbook (United States Department of Transportation, 1976) provides coupled, theoretical equations based upon Froude Number preservation. Solution of these equations by iteration yields the critical velocity. Froude Number modeling is applicable to situations, such as a fire emergency, where turbulent effects dominate and viscous effects can be neglected.

Vehicle induced ventilation: The phenomenon of aerodynamic drag from vehicles in tunnels can serve to assist or retard ventilation flow. Vehicles operating in a unidirectional tunnel, with no mechanical or natural form of ventilation, will produce a quantifiable piston effect. Poole (2002) provides relationships for estimating the drag effect associated with traffic in tunnels based on factors such as the area of the tunnel, area of the vehicles, mean traffic speed, vehicle form factor and the number of vehicles.

Jet fans: These fans are freestanding axial flow devices with an open inlet and outlet. Similar to booster fans in mines, jet fans are broadly used in many unidirectional road tunnels, and are also selectively used in other transit tunnels to assist primary fans. They offer a cost effective alternative or supplement to primary fans because they do not require the installation of a dedicated inlet and exhaust duct system. Jet fans are specifically designed for maximum efficiency in a freestanding condition, rather than when operating against a system pressure. The fans are typically rated in terms of the thrust applied to the air. A longitudinal airflow is induced due to the pressure rise caused by the fan. The fan creates thrust by ejecting a jet of high velocity air into the tunnel. As this jet decelerates, it transfers its energy to the tunnel air (kinetic energy to static energy), causing a pressure rise equal to the fan thrust divided by the cross-sectional area. An important consideration in the installation of jets fans is their position relative to each other and to the tunnel structure. Jet fans should ideally have at least 2 times the fan diameter between centers when mounted in parallel, and should be at least 10 tunnel hydraulic diameters apart when mounted in series. Deceleration of the air jet occurs gradually, and if the longitudinal distance is insufficient, the deceleration will be incomplete, such that the increased air velocity will affect the performance of the downstream fan(s). Jet fan efficiency is also affected by the proximity of the fan to the tunnel walls and ceiling.

4 Simulation Software

Software applications used for the design of tunnel ventilation systems fall into two general categories: one-dimensional, also known as network analysis, and two or three-dimensional CFD. In network analysis, the properties of air (velocity, pressure, temperature) are considered to be homogeneous across a transverse tunnel section taken at any location in the system. This is an acceptable simplification when considering systems in which the airflows are primarily longitudinal such as a tunnel). Consideration of more complex three-dimensional spaces such as underground stations often requires the use of CFD techniques, particularly when modeling fires.

4.1 One-Dimensional Analyses

One-dimensional analysis is used extensively in tunnel ventilation design. The software tools allow integrated modeling of the aerodynamic, thermodynamic, and fire scenarios associated with subsurface airways. An example is the freely-distributed Subway Environment Simulation (SES) Computer Program, developed by the United States Department of Transportation, Federal Transit Administration. This software allows dynamic simulation of trains (piston effect), and provides output for air velocity, temperature, and humidity. The program also computes cooling and heating capacities required to satisfy environmental criteria, and the long-term effect of the system on the temperature of the surrounding strata.

Other computational sequences are incorporated to model the effects of a fire. These effects include:

- Throttling effect on the ventilating airflow due to rapid expansion of the air flowing past the fire.
- Viscous pressure losses due to the fire.
- Increase of wall surface temperature downstream of the fire and the impact that this has on the airflow.
- Heat transfer processes associated with fire.
- The effect of the elevated air temperature on the performance of downstream fans.

4.2 CFD and Evacuation Software (3-Dimensional)

CFD techniques are increasingly used to model fires. They allow for a more detailed representation of the behavior of a fire and the environment in which it occurs. Unlike network analysis, where it may be necessary to compare an achieved airflow velocity against an independently calculated critical velocity to determine if back-layering will occur, CFD analysis is able to directly predict movement of hot smoke and fire gases based upon first principles.

Figures 4 and 5 show visibility plots for a fire simulation conducted for a typical modern subway station. The outline of the station can be seen in Figure 4, with visibility contours plotted for a vertical slice taken through the fire and along the length of the station. Figure 5 shows visibility at head height above the platform level of the station, as seen in plan view. The different plots represent different simulation and evacuation times.

The coupling of CFD fire modeling with virtual reality software and evacuation simulators allows visualization of the processes taking place during these complex events.

This relatively new level of visualization, in addition to being a valuable design tool, is helpful in the development of emergency procedures and can be used to improve operator training.

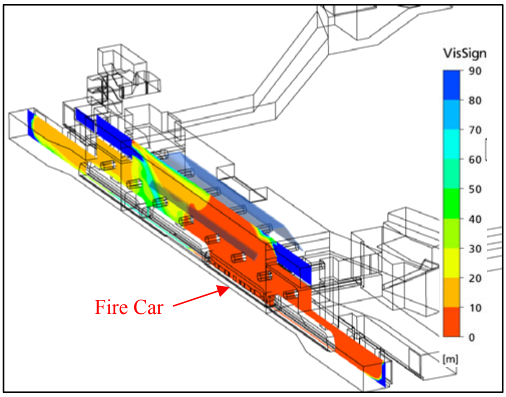

Figure 4. Visibility contour plot for fire in a subway station: vertical slice along the station.

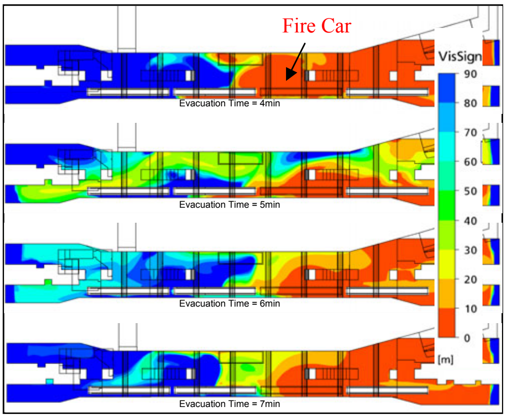

Figure 5. Visibility contour plot: horizontal slices for different evacuation times.

5 Conclusions

This paper has provided a broad overview of the history of fires in tunnels with discussion on some of the factors and decisions involved in the design of the fire safety systems to deal with such events.

The design of fire-life safety systems for public subsurface facilities is a complex process. There are multiple parties involved, including the agency/authority/operator, fire department, responsible designers, project sponsors, and in many cases associated entities such as insurance underwriters and unions. There will always be a focus on the improvement of standards and systems associated with the design and operation of fire control/smoke management systems in existing and new facilities. History has shown that there will be immediate and very public attention given to fires in public tunnels, and the safety systems will continue to come under intense scrutiny.

References

Bechtel/Parsons Brinckerhoff, 1995. *Memorial Tunnel Fire Ventilation Test Program, Comprehensive Test Report*, Prepared for the Massachusetts Highway Department.

Duckworth I.J. and Newman D.G., 2002. Application of Tunnel Ventilation Concepts to Mine Ventilation Design, *Proceedings of the North American/Ninth U.S. Mine Ventilation Symposium*, Published by A.A. Balkema Publishers, Netherlands, pages 219-226.

Duckworth I and Miclea P., 2007. Emergency Ventilation Systems Upgrade – A Journey from Wishful Thinking to Reality, *Proceedings First International Tunnel Safety Forum for Road and Rail*, Published by ITC Ltd, ISDN 1-901808-26-2, pages 37-46.

European Parliament, 2004. *Directive 2004/54/EC of the European Parliament and of the Council on Minimum Safety Requirements for Tunnels in the Trans-European Road Network.*

Miclea P. and Duckworth I., 2007. Current Trends in Fire Detection, Instrumentation and Suppression in Rail and Road Tunnels – A Pre-Requisite for Effective Emergency Response, *Proceedings First International Tunnel Safety Forum for Road and Rail*, Published by ITC Ltd, ISDN 1-901808-26-2, pages 25-35.

National Fire Protection Association, 2008. NFPA 502, 2008 Edition, *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*, Published by the National Fire Protection Association.

National Fire Protection Association, 2007. NFPA 130, 2007 Edition, *Standard for Fixed Guideway Transit and Passenger Rail Systems*, Published by the National Fire Protection Association.

PIARC Committee on Road Tunnels, 1995. *Vehicle Emissions, Air Demand, Environment and Longitudinal Ventilation*, Published by the Permanent International Association of Road Congresses, 63 pages.

Poole G.F., 2002. Predicting Annual Energy Consumption for Longitudinally Ventilated Road Tunnels, *Proceedings of the North American/Ninth U.S. Mine Ventilation Symposium*, Published by A.A. Balkema Publishers, Netherlands, pages 411-429.

United States Department of Transportation, 1976. *Subway Environmental Design Handbook, Volume I, Principals and Applications*, 2nd Edition.