Impact of Tunnel Ventilation Systems and Structures on the Space Required for Underground Rail Stations

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1. Introduction

Since 2008 most of the world population lives in urban areas than in rural areas and the disproportion grows. There are more than 300 cities in the world with a population of over one million inhabitants and all of them require efficient, safe means of transportation. It is estimated that metropolitan railways transport more than 3 billion passengers per year, or more than 12 million per day [1]. The busiest systems in the world are those in Moscow, London, New York, Tokyo, Beijing, Mexico City and Sao Paulo.

New transportation systems are a permanent necessity of the growing metropolitan areas all around the world. They often require routes along the most densely built city arteries to reach clusters of office buildings or living quarters, particularly for existing, old cities, with an increased traffic demand and frequencies of train service.

Limited space for the required right of way and for new stations constitutes a major demand for designers and architects to better use the available space, requiring elaborate trade-off studies of what can and cannot be done.

Transit organizations must provide reasonable levels of life safety to passengers, operating staff, authorized visitors and responding personnel. Modern mass transit systems with underground stations require entrances from the street level, as well as shafts blended within the existing city architecture. The stations should be inviting for riders and enhance the city environment, as gateways to the communities.

Dedicated structures and spaces needed for tunnel and station ventilation represent an important part of the total envelope and of the cost of an underground station [2, 3]. For this reason it is imperative to integrate the ventilation system and structures in the station design, to ensure safety and security functions in order to achieve comfortable environment for passengers within all station areas and to maintain a high degree of safety for users and operators.

The engineering concepts and criteria for the design of the ventilation systems for mass transit organizations, as a main component of the overall station design and architecture, must comply with the aesthetic integration of transit stations, particularly in high-density city centers.

State-of-the art design of fire-life safety systems and security features must facilitate air circulation and smoke control in case of an underground fire. Provision of emergency exits for the expected (maximum) occupancy that can be protected (smoke-free) in case of a fire should be incorporated in the design.

Transit stations are normally designed with fan shafts and fan plants attached to the station (at the end of the platform, with the shafts 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) or as fan shafts (by closing the dampers on the relief section of the shaft). In some cases, where the distance between stations is long, reducing the efficiency of station fans in case of an emergency in the middle of the
tunnel, mid-tunnel fans are provided, also. This scheme presents significant advantages compared with
the others, but higher cost, yet, for new subway systems or extensions to existing systems, the additional
cost for the inclusion of such dedicated emergency ventilation systems can be justified [4, 5].

2. Station functions and design considerations

2.1 Design approach. A consistent design concept during all design phases requires inter-disciplinary
communication between various engineering disciplines: structural, civil, architectural, mechanical,
electrical, and safety engineers. New systems should be designed with sufficient flexibility for growing
capacity and capable to absorb risk factors brought by reaching maximum utilization, including the
changes in operating modes and threats associated with unexpected crowds and behavior.

The design should consider passenger flow in normal and emergency conditions, based upon patronage
calculations and evacuation requirements, particularly in case of a fire. Adequate space for electrical and
mechanical equipment, station and emergency ventilation equipment and numerous other components
should be considered from the conceptual design phase on. As the design progresses, these factors
change and the station layout must often change accordingly.

Suitable evacuation routes and spaces through the station towards the exits must be provided, to
facilitate this movement, including sufficient space in front of the stairs and escalators. The width of the
stairs and escalators should consider not only the accommodation of the maximum number of people, but
also maximum air velocity during an evacuation, as part of the design criteria.

The main design factors that govern sizing a transit station consist of the existing geotechnical conditions,
available right of way and tunnel engineering factors governing the alignment and depth, as well as
technical engineering for entrance access. These considerations and applicable safety codes determine
station size and shape of the station final design. Other factors include station occupant loads, size and
location of stairs and escalators, configuration and location of entry gates, ticketing machines, horizontal
and vertical circulation, platform length and width for train boarding, fire-fighters access, etc.

In addition to the space required for passengers access to the platform areas and for orderly boarding or
getting off trains, significantly large spaces are required for the ancillary functions of the station.

The mechanical and electrical equipment in an underground station require large amounts of very
valuable space within the station. These systems are necessary to maintain the operations of both trains
and stations. They also support the safety of the passengers and provide protection during emergency
situations. All these systems necessary to insure the quick and safe evacuation of the station should be
given the highest priority.

The large air distribution fans at both ends of the station are designed to operate during a fire emergency
to push smoke away from the source of fire allowing passengers to evacuate the area. These fans are
also designed to pull smoke away from the exiting patrons and carry it through ducts and shafts out of the
station, up to the surface and prevent recirculation through entrances. This station fans capability is
paramount in emergencies, given the fact that in case of a train fire in the tunnel, most operators require
that driver should not stop the train, but continue on to the next station for evacuation and fire fighting.

Newer stations often contain other equipment to protect the patrons, such as fire sprinkler systems to
protect the patrons by suppressing fires in public areas in case of small fires along the platform, as well
as deluge systems at the track levels that release large volumes of water to the underside of a train in the
event of a fire.

2.2 Interaction between stations, tunnels and shafts. To the extent possible, a rail transit subway
system should be designed to take advantage of natural ventilation caused by the train operation, since
air generally moves in the direction of train travel. The positive pressure in front of a train moves air
through tunnels and station entrances; the negative pressure behind the train induces airflow through
these same openings. Considerable short-circuiting of air flows occurs in subway structures when two
trains traveling in opposite directions pass each other. Such short-circuiting of airflow between trainways
might occur in both station and tunnels with nonporous walls through cross-passageways or other
unrestricted airways. To reduce these negative effects, ventilation shafts are customarily placed in the

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tunnels, preferably just outside the station ends. During normal operation these shafts in the approach tunnel operate for pressure relief ("blast shafts") allowing part of the air pushed ahead of the train to be expelled through them. Thus the structures work as “relief shafts” in the departure tunnel, relieving the negative pressure created during the departure of the train and inducing an intake of outside air through the shaft. The direct effect of this concept is a reduced airflow through station entrances, translated in a more comfortable environment for passengers. The emergency fans and their connecting ducts require large spaces either within or adjacent to the station envelope (Figures 1, 2).

![Figure 1 Considerable space for a fan plant](image1)

![Figure 2 Large axial fan (reversible)](image2)

2.3 Station costs. Due to the high cost of underground excavation and construction, the size of the station must be kept to absolute minimum, without sacrificing the overall functions and especially the life safety requirements. There are considerable differences in capital costs from country to country, often from region to region and, therefore, it is difficult to provide specific costs. On the other hand, the costs vary between stations built by the cut-and-cover (C&C) method, mined excavation method, or by enlarging a tunnel previously created by a tunnel boring machine (TBM). Station appendages, such as fan rooms, impact the right-of-way (ROW) and consequently represent a major cost item as well.

Station costs tend to be generally several times higher than tunnel costs per unit of length, due to the added space for platforms, as well as to the auxiliary space for fan rooms and ducts. Therefore, it is important for the designer to contain the size of the station box to a minimum.

The emergency fan rooms require space for fans and their appurtenances (transitions, sound attenuators, ducts, control panels, etc). Most of the times the axial, reversible fans are installed horizontally, often in parallel, with sufficient space around for maintenance. There are cases, particularly for deep stations, when the fans can be installed vertically, in shafts, thus reducing the space in the stations. Maintenance and access, in general, should be carefully considered for this option. Trade-off studies are usually performed to account for all advantages and disadvantages, as well as life-cycle costs for the two options.

3. Tunnel ventilation system design criteria

There are relatively few regulations and criteria for rail tunnel 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 [6]. Many of the subway transit systems in existence today have been designed and built with ventilation features adequate for normal train operation at the time, but their design does not always consider stringent criteria for such emergency conditions as a train fire in a tunnel or at station.

Recently US Secretary of Transportation Ray LaHood has called for the Federal Transit Administration (FTA) to add safety oversight authority for light and heavy rail systems as well as bus systems. Initial press reports indicate that under the administration’s proposal, states would need to pass safety certification programs, demonstrate that they have adequately trained employees and possess the financial independence and authority to compel compliance from the safety systems. Further, FTA would assume direct oversight for states that decided to opt out of monitoring. FTA would also take over for state organizations that it determined to be inadequate.
3.1 Current concepts and design approach. Current concepts of sustainable design for tunnel ventilation systems consider the worst-case scenarios that might happen during all operational conditions: normal, congestion and fire emergencies [7]. There is a clear distinction between the requirements for passengers’ comfort during normal train operation, as compared with what needs to be done to maintain safe operation in case of traffic congestion in the tunnel, or when an accidental vehicle fire happens in a tunnel or station. In most cases the required level of safety is achieved by the natural ventilation created by moving trains that usually ensures air velocities in enclosed stations and trainways greater than 0.75 ms\(^{-1}\) (150 fpm) required by the current safety standard.

The U.S. National Fire Protection Association’s Standard for Fixed Guideway Transit and Passenger Rail Systems known as NFPA 130 [8] as well as the American Society of Heating, Refrigerating and Air Conditioning Engineers ASHRAE Handbook - HVAC Applications, Chapter 13 – Enclosed Vehicular Facilities (2007) [9] and the Air Movement and Control Association (AMCA) 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 safety regulations [10, 11].

These general design criteria are often supplemented by specific requirements and practice demonstrated by experience in a certain industry or jurisdiction. Project specific design criteria are generally prepared by the owner’s consultant, in coordination with the authority having jurisdiction (AHJ), as an expansion of the DOT, NFPA, ASHRAE and AMCA standards.

The environment in a subway station during normal operation should provide a smooth transition between outside conditions and those in the transit vehicles. ASHRAE and SEDH recommend that a minimum amount of outside air should be introduced into tunnels and stations to dilute gaseous contaminants. There are no limitations for maximum air flow, other than the nuisance concerns based on which peak air velocities in public areas should be limited.

Emergency conditions result from a malfunction of the transit vehicle, such as a stopped train on fire in a tunnel, disrupting traffic and requiring passenger evacuation. For such conditions the ventilation system must be capable to clear the smoke and hot gases and to maintaining a safe evacuation path to a point of safety, while allowing fire-fighting operations. The minimum air velocity in the affected tunnel section should be sufficient to prevent the smoke from backlayering (i.e., flowing in the upper cross-section of the tunnel in the direction opposite to the forced outside ventilation air). The maximum air velocity in the evacuation routes should not exceed 11 ms\(^{-1}\) (2200 fpm).

The ventilation system is sized for the worst emergency condition, which, most of the time is for a major fire; therefore, often the terminology refers to it as the emergency ventilation system (EVS) [12, 13]. In case of a tunnel fire the operation of the EVS must be activated to ensure a safe evacuation of passengers and to maintain tenable conditions along the evacuation route for the required evacuation time (sometimes called ‘time of tenability’).

When stations are designed with an EVS, the fan shafts can be located either inside the underground station’s envelope, or outside at grade attached to tunnels. Fan shafts are usually 10 to 20 m (30 ft to 60 ft) away from the platform’s end. As mentioned above, mid-tunnel fan shafts may be necessary where the distance between stations is long, reducing the efficiency of station fans in case of an emergency in the middle of the tunnel. While there are advantages and disadvantages associated with either system, however, in most cases the driving factor is the capital cost (usually lower for end of station shafts).

Given the diversity of station design, it would be difficult to even attempt a recommendation for the best emergency ventilation method. One simple principle should be implemented, however: in case of a major vehicle fire in the station, the smoke and heat should be controlled in such a way that at least one safe evacuation route is maintained. To achieve this objective, the design should incorporate means and procedures to prevent smoke migration in the mezzanine, or other public areas along the evacuation route, other than the platform where fire originated or close to the fire tunnel section.

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 (CFD) computer techniques.

One requirement for the EVS to be considered in the station design and shaft location is the need for regular testing of emergency fans (noise considerations) and evacuation exercises that often may affect the neighborhood. Where available, parks, squares, vegetation landscape are preferred locations on surface for ventilation shafts and their house heads.

The design of the ventilation shafts should consider other factors, as well, including the size (cross-sectional area) sufficient for the maximum amount of airflow expected, smooth lining to minimize air friction (and fan power), cross-sectional area (no obstructions or sudden changes), raised shaft head on surface to minimize impact on environment and reasonable distance from station entrances or buildings (to prevent air recirculation and pollution of nearby facilities). These considerations should be incorporated in the initial tunnel design.

3.2 Smoke and heat control in case of a vehicle fire. Fires in tunnels and underground stations may be caused by accidents, electrical faults, sabotage or vandalism. Priorities following a fire are rescuing people and saving lives, extinguishing the fire, preserving the structure, investigating the cause, and then undertaking modifications or implementing procedures to prevent a recurrence. The consequences of fires in tunnels are often serious, and there may be deaths and injuries. Burning fuel, oil, plastics, and some paints cause dense smoke and toxic fumes that hamper visibility and can produce death by asphyxiation. Temperatures may reach more than 1,000°C (1800°F), causing severe structural damages.

The emergency ventilation and evacuation procedures that are part of this planning are important because the smoke and other fire products have a tendency to move upwards out of the stations and contaminate normal passenger exit routes. The emergency ventilation system must be able to support evacuation by providing reliable, well-defined routes out of the tunnel or station. The evacuation routes must correspond to the airflow patterns created by the operation of emergency ventilation fans.

To facilitate safe and orderly evacuation of patrons from the station, signage, graphics, exit lights, a public address system and other components are streamlined into the design process. The design of the EVS, local mechanical ventilation and fire-life safety systems in the facility are to be performed in coordination.

3.3 Specific ventilation requirements for stations. The environment in a subway station should provide a smooth transition between outside conditions, those on the platform and in the transit vehicles.

There is inconsistency in the way various transit agencies design and build the stations and shaft houses. There are stations without any mechanical ventilation (except natural ventilation), stations with a ventilation system to control the environment under normal conditions only (either above platform exhaust system, or under platform exhaust system - UPE), stations with an emergency ventilation system and stations with more than one system (usually UPE and emergency systems).

California Building Code contains specific requirements for separation of shafts and other openings to prevent smoke recirculation, restricting the termination of shafts at grade or on roadways. The code does not contain specific requirements or recommendations for the height of the shaft stake-house [14].

For normal conditions, minimum 0.0035 m³/s (7.5 cfm) outside air per person is recommended to dilute gaseous contaminants and maximum air velocities in public areas should not exceed 5 m/s¹ (1000 fpm). For passengers comfort the platform air temperature should not exceed the ambient temperature by more than 5°C.

4. Ventilation equipment and structures

As stated earlier, in case of a vehicle fire in a tunnel, the EVS must be able to ventilate the maximum fire at each and every possible location in the tunnels or at the stations to support evacuation by maintaining the evacuation routes clear of smoke and heat, knowing that visibility influences the evacuation speed which is critical in saving lives. EVS should be able to control the spread of smoke by creating an air stream with a velocity past the fire higher than the velocity required to prevent smoke backlayering.
NFPA 130 standard, as well as some of the state building codes, specify that during an emergency all the occupants of the station boarding platform must be able to evacuate the platform within four minutes and that all occupants of the platform/station must be able to exit the station within six minutes. This requirement has a significant impact on the design of stations.

To achieve the required safety functions, the EVS must have a capacity to meet the demands of a 'worst-case' scenario, i.e., for the maximum fire size and the largest population to be evacuated. Properly designed emergency fan plants (Figure 3) play the main role in providing for a safe evacuation route and for protecting the infrastructure of the transit system. A typical fan room size for two axial, fully reversible fans of 120 m$^3$/s (250 cfm) each would be 14m long, 14m wide and 5.8m high (46'L x 46'W x 19'H), with a 2.4m (8'W) equipment door between fans. The room size is based on 4.3m x 4.3m x 2.15m (14'W x 14'H x 7'L) sound attenuators at both ends. In addition, an electrical room of 7m x 3m x3m (22'L x 10'W x 10'H) for the fan damper control panel and for the two starters is usually required. Other auxiliaries include an emergency management panel room, near the station entrance and a substation room.

5. Tunnel ventilation system integration with station design

To protect the public and facilitate exiting the station during an emergency, the station fire-life safety system also contains smoke and heat detection and public address systems with pre-recorded announcements, as well as closed circuit TV monitoring. All the critical equipment and lighting in the station is designed to run on an emergency power source, if normal power fails for any reasons.

In some cases, particularly for multi-level stations, a separate smoke exhaust system is provided for station emergencies. This system generally caters for small fires, such as waste fires, or small arsons on the platform level. They cannot, however, control the heat and smoke generated by a large vehicle fire, for which large tunnel emergency fans are recommended and must be sized accordingly.

In addition to the emergency ventilation system for the tunnels and station platforms, a fresh air supply system may be required for station during normal operation, particularly to spaces not ventilated by the piston effect of the moving trains.

Sprinklers are not considered for tunnels; where installed, there are serious concerns for activating the sprinkler systems during a major vehicle fire requiring evacuation, when the platforms become slippery and may impede on the evacuation time. To alleviate this risk, the protocol is to activate the sprinklers after the evacuation is complete, which reduces the expected effect of controlling the temperature by cooling the fire. Standby pipes (either dry or wet) are normally installed and provided with fire-fighter hook-ups at pre-established locations [15].
One important aspect of fire-life safety in tunnels and underground stations is the need to maintain power for the fans and lighting during all the time. NFPA 130 requires that emergency fans be powered by two separate, independent sources, in the event of a power outage. These sources may be electric power from two different substations, or an electric source from the main grid and a local generator.

As part of the overall fire-life safety and evacuation procedures, the tunnels and underground stations must be provided with detection, alarm, and annunciation systems, for emergency warnings and the capability to provide instructions to passengers [16].

Traction power and other electrical systems utilize large amounts of ancillary spaces that must be ventilated to maintain operating temperatures. These spaces, usually large components of the entire system, have to be accessible from outside the station so they can be replaced quickly, in order to maintain system operations. Given the fact that substations normally require cooling the equipment, their ventilation systems should be designed to discharge the heat to the ambient, rather than into the tunnel.

6. Conclusions

New mass transportation systems of increasing capacities are a permanent necessity for hundreds of metropolitan areas all around the world. Passengers expect the transit system they use to be inviting and safe, in case of accidents (such as fires).

Although there is significant progress in reducing the risk of fire, particularly in the newly designed and built systems, by hardening the vehicles, preventing, detecting, and suppressing techniques, the risk and the cost of a major fire in tunnels or underground stations still exists and may be extremely high.

Transit stations must provide not only quick passengers access to, or exit from the trains, but comfort during normal operation and safe evacuation in emergency situations, as well. For underground stations, this function becomes more critical, given space limitations and the costs involved, with the ventilation structures accounting for up to one third of the entire station volume.

Fire-life safety criteria, standards, regulations, guidelines, and recommendations vary widely, from country to country, sometimes even nationally. The situation becomes more critical due to the global economy and increasing worldwide tourism, with multi-national companies often involved in both design and construction of subways in other countries. With the increase in tourism comes the risk of visitors becoming victims of a tunnel fire in a foreign land. Thus, international law becomes more and more applicable to transit projects all over the world.

There is no single method to provide protection to passengers and to avoid material damages. However, a coordinated effort in the design of an integrated system that satisfy all safety requirements, as well as the combination of prevention techniques and use of mechanical emergency ventilation systems are becoming the norm.

The building codes and standards that govern the design of underground transit stations are very important due to the unusual environmental and logistical issues that are encountered in such facilities. The high cost of underground excavation and construction dictates that the size of stations must be kept to an absolute minimum.

Transit systems are a reality of the present and the future. They are not only infrastructure investments, but public assets of civic pride. It is our duty, as designers and constructors, to encourage their use and protect the users.
REFERENCES:


