CHAPTER 15

ENCLOSED VEHICULAR FACILITIES

ENCLOSED vehicular facilities include buildings and infrastructure through which vehicles travel, are stored, or are repaired, and can include vehicles driven by internal combustion engines or electric motors. Ventilation requirements for these facilities are provided for climate and temperature control, contaminant level control, and emergency smoke management. Design approaches for various natural and mechanical ventilation systems are covered in this chapter.

The chapter is structured to address general tunnel issues first and then address the unique aspects of rail and road tunnels, rail stations, bus garages, bus terminals, and enclosed spaces for equipment maintenance later in the chapter. Finally, information on applicable ventilation equipment is presented.

1. TUNNELS

Transport tunnels are unique, in that vehicles travel at normal speeds, possibly carrying cargo (which may be unknown in road tunnels), and may include the traveling public (as passengers and/or motorists) during both normal and emergency operations. A tunnel is a linear-configured facility, as opposed to most buildings, which are typically more rectangular. This concept is important when confronting the need to fight a fire within a tunnel. A tunnel cannot be compartmentalized as readily as a building, which means the fire can only be fought from within the actual fire zone. Limited access and compartmentation create difficulties with containing and suppressing a fire. This combination of circumstances requires unique design approaches to both normal and emergency operation.

Tunnel Ventilation Concepts

Tunnel ventilation must accommodate normal, congested, and emergency conditions. In some cases, temporary ventilation may also be necessary.

Normal Mode. Normal ventilation is required during normal operations to control temperature, provide comfort, or control level of pollutants in the facility during normal operations and under normal operating conditions, primarily to protect the health and provide comfort for the patrons and employees.

Congested Mode. Congested ventilation is required during service periods where traffic is slow moving, leading to a reduction or elimination of piston effect. The goals are the same as for normal mode.

Emergency Mode. Emergency ventilation is required during an emergency to facilitate safe evacuation and to support firefighting and rescue operations. This is often due to a fire, but it can be any nonnormal incident that requires unusual control of the environment in the facility. This includes control of smoke and high temperature from a fire, control of exceedingly high levels of contaminants, and/or control of other abnormal environmental conditions.

Temporary Mode. Temporary ventilation is needed during original construction or while maintenance-related work is carried out in a tunnel, usually during nonoperational hours. The temporary ventilation is typically removed after construction or after the maintenance work is completed. Ventilation requirements for such temporary systems are specified by either state or local mining laws, industrial codes, or the U.S. Occupational Safety and Health Administration (OSHA) and are not addressed specifically in this chapter.

Tunnel Ventilation Systems

There are two categories of ventilation systems used in most tunnels: natural and mechanical.

Natural Ventilation. Naturally ventilated facilities rely primarily on atmospheric conditions to maintain airflow and provide a satisfactory environment in the facility. The chief factor affecting the facility environment is the pressure differential created by differences in elevation, ambient air temperature, or wind effects at the boundaries of the facility. Unfortunately, most of these factors are highly variable with time, and thus the resultant natural ventilation is often neither reliable nor consistent. If vehicles are moving through a tunnel-type facility, the piston effect created by the moving vehicles may provide additional natural airflow.

Mechanical Ventilation. A tunnel that is long, has a heavy traffic flow, or experiences frequent adverse atmospheric conditions requires fan-based mechanical ventilation. Among the alternatives available are longitudinal and transverse ventilation.

Longitudinal Ventilation. This type of ventilation introduces or removes air from the tunnel at a limited number of points, primarily creating longitudinal airflow along its length. Longitudinal ventilation can be accomplished either by injection, using central fans, using jet fans mounted in the facility, or a combination of injection and extraction at intermediate points.

Transverse Ventilation. Transverse ventilation uses both a supply duct system and an exhaust duct system to uniformly distribute supply air and collect vitiated air throughout the length of the facility. The supply and exhaust ducts are served by a series of fixed fans, usually housed in a ventilation building or structure. A variant of this type of ventilation is **semitransverse ventilation**, which uses either a supply or exhaust duct, not both. The balance of airflow is made up via the tunnel portals.

Design Approach

General Design Criteria. The air quality and corresponding ventilation system airflow requirements in enclosed vehicular spaces are determined primarily by the type and quantity of contaminants that are generated or introduced into the tunnel and the amount of ventilation needed to limit the high air temperatures or concentrations of these contaminants to acceptable levels for the specific time exposures.

Normal and Congested Modes. The maximum allowable concentrations and levels of exposure for most contaminants are determined by national governing agencies such as the U.S. Environmental Protection Agency (EPA), OSHA, and the American Conference of Governmental Industrial Hygienists (ACGIH).

The contaminant generators can be as varied as gasoline or diesel automobiles, diesel or compressed natural gas (CNG) buses and trucks, and diesel locomotives. Even heat generated by air conditioning on

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electric trains stopped at stations and the pressure transients generated by rapid-transit moving trains can be considered contaminants, the effects of which need to be mitigated.

Emergency Mode. Design provisions may be necessary to manage smoke and other products of combustion released during fires to allow safe evacuation, to support fire fighting and rescue operations, and to protect the tunnel structure and station infrastructure during fires (Bendelius 2008).

In designing for fires, the design fire scenario and associated fire heat release rate needs to be quantified. Depending on the level of analysis, the generation of smoke and other products of combustion may also need to be quantified. As a minimum, design for life safety during fires must conform to the specific standards or guidelines of the National Fire Protection Association (NFPA), where applicable. NFPA's ventilation requirements are for systems to maintain a "tenable environment along the pathway of egress from the fire." NFPA *Standard* 130 defines a tenable environment as "an environment that permits self-rescue of occupants for a specific period of time"; NFPA *Standard* 502 includes a similar definition.

Other NFPA codes and standards; ICC (2009a, 2009b, 2009c) building, mechanical, and fire codes; and other statutory requirements may apply. Separation and pressurization requirements between adjacent facilities should also be considered.

Temporary. A temporary mode may be necessary during construction or other special condition.

Technical Approach. The technical approach differs depending on facility type; however, there are many similarities in the initial stages of the design process.

Determining the length, gradient, and cross section for tunnels is an important first step. Establishing the facility's dynamic clearance envelope is of extreme importance, especially for a tunnel, because all appurtenances, equipment, ductwork, jet fans, etc., must be located outdoor the envelope, and this may eventually determine the type of ventilation system used.

Vehicle speeds, vehicle cross-sectional areas, vehicle design fire scenarios, and fuel-carrying capacity are important considerations for road tunnels, as are train speeds, train headway, and rail car combustibility and design fire scenarios for rapid transit and railroad tunnels.

Types of cargo to be allowed through the facility, and their respective design fire scenarios, should be investigated to determine the ventilation rates and the best system for the application. Similarly, for railroad tunnels, it should be determined whether passenger or freight or both types of trains will be using the facility and if the passenger trains will be powered by diesel/electric power or by electric traction power.

The emergency ventilation approach must be fully coordinated with the overall fire protection strategy, the evacuation plan, and the emergency response plan, providing a comprehensive overall life safety program for the tunnel or station. Egress systems must provide for safe evacuation under a wide range of emergency conditions. The emergency response plan must help facilitate evacuation and allow for appropriate response to emergencies.

Rail and bus stations are large unique structures designed to allow efficient movement of large populations and to serve occupants that often arrive in large groups. Stations can be below ground, above ground, or at grade. Although each type of station poses specific challenges, underground facilities tend be the most challenging. Stations can be further complicated by connections to non-transit structures (Tubbs and Meacham 2007).

Rail and road tunnels pose a different set of evacuation challenges. These facilities are long, narrow, and underground, often with limited opportunities for stairwells to grade. The linear nature limits initial evacuation, which can pose challenges to the ventilation design. Further, the trackway in rail tunnels can be a dangerous environment for untrained occupants.

The ventilation and other protection systems must support the evacuation plan. NFPA *Standards* 502 and 130 provide specific criteria for components of the life safety and evacuation systems, but are not universally adopted by authorities. Where road and rail infrastructure interface with buildings, the *International Building Code*® and *International Fire Code*® may apply. Several documents are available to provide additional guidance on life safety concepts, evacuation strategies, and calculation methodologies (Bendelius 2008; Colino and Rosenstein 2006; Fruin 1987; Gwynne and Rosenbaum 2008; Proulx 2008; Tubbs and Meacham 2007).

Critical Velocity. Manual calculations and resources for the emission and combustion data are given in the respective sections for each enclosed vehicular facility type. A first step in determining the order of magnitude for the ventilation rate required to control the movement of the heat and smoke layer generated by a fire in a tunnel is to apply the critical velocity criterion. This approach is described here, and can be used for all types of tunnel applications.

The simultaneous solution of Equations (1) and (2), by iteration, determines the critical velocity (Kennedy et al. 1996), which is the minimum steady-state average bulk velocity of ventilation air moving toward the fire needed to prevent backlayering:

$$V_C = K_1 K_G \left(\frac{gHq}{\rho c_p A T_F} \right)^{1/3} \tag{1}$$

$$T_F = \left(\frac{q}{\rho c_p A V_C} \right) + T \tag{2}$$

where

V_C = critical velocity, m/s
T_F = average temperature of fire site gases, K
K_1 = 0.606
K_G = grade factor (see Figure 1)
g = acceleration caused by gravity, m/s^2
H = height of duct or tunnel at fire site, m
q = heat that fire adds directly to air at fire site, kW
ρ = average density of approach (upstream) air, kg/m^3
c_p = specific heat of air, kJ/(kg·K)
A = area perpendicular to flow, m^2
T = temperature of approach air, K

It is usual to study several alternative ventilation schemes, each using different variants and/or combinations of ventilation systems (longitudinal, transverse, etc.). Some types of systems, such as fully transverse, are almost exclusively used on road tunnels only.

When selecting ventilation equipment and the number of fans and types of drives, consideration should be given to efficiency, reliability, and noise. Most of these equipment attributes are reflected in a life-cycle cost analysis of the alternatives.

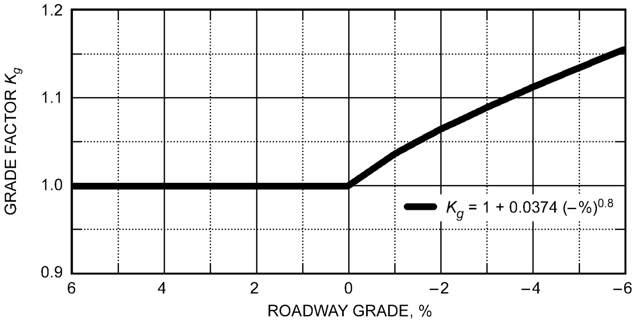


Fig. 1 Roadway Grade Factor

If the effectiveness of the system to provide for fire life-safety conditions is not evident from the manual analysis or one-dimensional computer models such as subway environment simulation (SES), the designer should investigate using a computational fluid dynamics (CFD) program to accurately determine the smoke and temperature distribution in both the steady-state and transient conditions.

Computer Modeling and Simulation. The applicable NFPA standards for road tunnels (NFPA *Standard* 502) and for railroad rapid transit tunnels (NFPA *Standard* 130) require engineering analysis for tunnels greater than a certain length, to prove that the smoke and heat layer is controlled. Often the best way to show that the requirements are met is by using a CFD program with post-processing capabilities that feed the results into another program capable of producing a still picture and/or animated graphical representation of the results. All the commonly used computer programs and their specific capabilities are discussed in the following paragraphs.

SES. The predominant worldwide tool for analyzing the aerothermodynamic environment of rapid transit rail tunnels is the Subway Environment Simulation (SES) computer program (DOT 1997a). SES is a one-dimensional network model that is used to evaluate longitudinal airflow in tunnels. The model predicts airflow rates, velocities and temperatures in the subway environment caused by train movement or fans, as well as the station cooling loads required to maintain the public areas of the station to predetermined design conditions throughout the year. This program contains a fire model that can simulate longitudinal airflow required to overcome backlayering and control smoke movement in a tunnel. Output from the SES can be applied as boundary or initial conditions for three-dimensional CFD modelling of the tunnel and station environments. The SES program is in the public domain, available from the Volpe National Transportation Systems Center in Cambridge, MA.

TUNVEN. This program solves coupled one-dimensional, steady-state tunnel aerodynamic and advection equations. It can predict quasi-steady-state longitudinal air velocities and concentrations of CO, NO_x, and total hydrocarbons along a road tunnel for a wide range of tunnel designs, traffic loads, and external ambient conditions.

The program can also be used to model all common road tunnel ventilation systems (i.e., natural, longitudinal, semitransverse, and transverse). The user must update emissions data for the calendar year of interest. The program is available from the National Technical Information Service (NTIS 1980).

Computational Fluid Dynamics (CFD). CFD software can model operating conditions in tunnels and stations and predict the resulting environment. In areas of geometrical complexity, CFD is the appropriate tool to predict three-dimensional patterns of airflow, temperature, and other flow variables, including concentration of species, which may vary with time and space. Computational fluid dynamics software is the design tool of choice to obtain an optimum design, because experimental methods are costly, complex, and yield limited information.

SOLVENT. SOLVENT is a specific CFD model developed as part of the Memorial Tunnel Fire Ventilation Test Program for simulating road tunnel fluid flow, heat transfer, and smoke transport. SOLVENT can be applied to all ventilation systems used in road tunnels, including those based on natural airflow. The program results have been validated against data from Massachusetts Highway Department and Federal Highway Authority (MHD/FHWA 1995).

Fire Dynamics Simulator (FDS). FDS is a Computational Fluid Dynamics (CFD) model of buoyancy-driven fluid flow from a fire. A separate code called Smokeview is used to visualize data output from FDS. These applications can also be configured to model pollutant levels outdoor the portals and around the exhaust stacks of tunnels. Both of these public domain programs are under active development and can be obtained from National Institute of Standards and Technology (NIST).

Other CFD programs, both commercially available and in the public domain, have been used to model fire scenarios in road and rapid transit tunnels and stations, the list of which is too numerous to include here. The strengths and weaknesses of each program should be investigated beforehand, and validation of results against experimental data or an equivalent program is encouraged.

Tunnel Fires

Fires occurring in tunnels are more difficult to deal with than those occurring in one of the other enclosed vehicular facilities, in a normal building, or in the open. In a tunnel, firefighting is extremely complex, because access to the tunnel is difficult in the event of a fire. The fire cannot be fought from outdoor the tunnel, as can be done with a building; it must be fought from within the tunnel, often in the same space where the fire is burning.

Fires occur in tunnels far less frequently than in buildings; however, because of the unique nature of a tunnel fire, they are more difficult to suppress and extinguish and usually get more attention. There is a long list of tunnel fires; the most complete history of fires in tunnels exists for road tunnels, a partial listing of which is included in Table 1. Similar information is available for rail fires (Meacham et al. 2010).

Design Fires. Design fires form the base input for emergency ventilation design analyses and are defined in terms of heat release rate, species output, and soot yields as functions of time. A design fire scenario is an input parameter that defines the ignition source, fire growth on the first item, possible spread of fire to adjacent combustibles, interaction between the fire and the enclosure and environment, and eventual fire decay and extinction.

Limited data are available regarding the magnitude and severity of vehicle design fires. In the absence of more specific data, the information available provides first-order guidance in selecting an appropriate design fire for the evaluation of an enclosed vehicular facility such as a tunnel (road or rail) or station (bus or rail).

PIARC (1999) and NFPA *Standard* 502 provide summaries of vehicle fire tests. Additional information can be found in Atkinson et al. (2001), Ingason (1994), Joyeux (1997), and Mangs and Keski-Rahkonen (1994a, 1994b).

Fire Detection. Fire detection systems are necessary to alert tunnel operators of potential unsafe condition. There are a range of methods available to detect fire and smoke within road/rail tunnels and rail stations, including linear (line-type) heat detection, CCTV video image smoke detection, flame detection, smoke and heat detectors, and spot-type detection. Fire detection systems should be selected to support the fire safety goals and objectives and the overall fire safety program, which can include notifying occupants to allow for safe evacuation, modifying tunnel ventilation or operations, and notifying emergency responders.

NFPA *Standards* 130 and 502 provide general requirements for fire detections systems in transportation tunnels. These documents reference codes such as NFPA *Standard* 72, which provide design requirements for fire detection and occupant notification. Publications developed by the Road Tunnel Operation Technical Committee of PIARC (2007b, 2008) include specific guidance on the application of these systems. There have been several research projects that can also provide additional information to assist with developing detection system concepts and designs (Liu et al. 2006, 2009; Kashef et al. 2009; Zalosh and Chantranuwat 2003). Bendelius (2008) provides information on advantages and disadvantages and selection of fire detection methods in tunnels.

Road Tunnels

A road tunnel is an enclosed vehicular facility with an operating roadway for motor vehicles passing through it. Road tunnels may be underwater (subaqueous), mountain, or urban, or may be created by air-right structures over a roadway or overbuilds of a roadway.

Table 1 List of Road Tunnel Fires

					Damage		
Year	**Tunnel**	**Country**	**Length, m**	**Fire Duration**	**People**	**Vehicles**	**Structure**
1949	Holland	United States	2 550	4 h	66 injured	10 trucks 13 cars	Serious
1974	Mont Blanc	France/Italy	11 600	15 min	1 injured	—	—
1976	Crossing BP	France	430	1 h	12 injured	1 truck	Serious
1978	Velsen	Netherlands	770	1 h 20 min	5 dead 5 injured	4 trucks 2 cars	Serious
1979	Nihonzaka	Japan	2 045	159 h	7 dead 1 injured	127 trucks 46 cars	Serious
1980	Kajiwara	Japan	740	—	1 dead	2 trucks	Serious
1982	Caldecott	United States	1 028	2 h 40 min	7 dead 2 injured	3 trucks 1 bus 4 cars	Serious
1983	Pecorila Galleria	Italy	662	—	9 dead 22 injured	10 cars	Limited
1986	L'Arme	France	1 105	—	3 dead 5 injured	1 truck 4 cars	Limited
1987	Gumefens	Switzerland	343	2 h	2 dead	2 trucks 1 van	Slight
1990	Røldal	Norway	4 656	50 min	1 injured	—	Limited
1990	Mont Blanc	France/Italy	11 600	—	2 injured	1 truck	Limited
1993	Serra Ripoli	Italy	442	2 h 30 min	4 dead 4 injured	5 trucks 11 cars	Limited
1993	Hovden	Norway	1 290	1 h	5 injured	1 motorcycle 2 cars	Limited
1994	Huguenot	South Africa	3 914	1 h	1 dead 28 injured	1 bus	Serious
1995	Pfander	Austria	6 719	1 h	3 dead 4 injured	1 truck 1 van 1 car	Serious
1996	Isola delle Femmine	Italy	148	—	5 dead 20 injured	1 tanker 1 bus 18 cars	Serious
1999	Mont Blanc	France/Italy	11 600	—	39 dead	23 trucks 10 cars 1 motorcycle 2 fire engines	Serious
1999	Tauern	Austria	6 401	—	12 dead 49 injured	14 trucks 26 cars	Serious
2000	Seljestad	Norway	1 272	45 min	6 injured	1 truck 4 cars 1 motorcycle	—
2001	Praponti	Italy	4 409	—	19 injured	—	Serious
2001	Gleinalm	Austria	8 320	—	5 dead 4 injured	—	—
2001	Propontin	Italy	4 409	—	14 injured	1 car	—
2001	Gleinalm	Austria	8 300	—	5 dead 4 injured	—	—
2001	Guldborgsund	Denmark	460	—	5 dead 6 injured	—	—
2001	St. Gotthard	Switzerland	16 920	—	11 dead	2 heavy-goods vehicle	—
2002	Ostwaldiberg	Austria	—	—	1 dead	—	—
2003	44-France	France	618	—	2 dead	1 car 1 motorcycle	—
2003	Baregg	Switzerland	1 390	—	2 dead 21 injured	4 trucks 3 fire engines	Serious
2004	Baregg	Switzerland	1 080	—	1 dead 1 injured	1 car 1 truck	—
2005	Frejus	France-Italy	12 870	6 h	2 dead	4 trucks 1 fire engine	—
2006	Viamala	Switzerland	742	—	9 dead 6 injured	—	—

Source: PIARC (2007a, 2007b)

All road tunnels require ventilation to remove contaminants produced during normal engine operation. Normal ventilation may be provided by natural means, by traffic-induced piston effects, or by mechanical equipment. The method selected should be the most economical in both construction and operating costs.

Ventilation must also provide control of smoke and heated gases from a fire in the tunnel. Smoke flow control is needed to provide an environment suitable for both evacuation and rescue in the evacuation path. Emergency ventilation can be provided by natural means, by taking advantage of the buoyancy of smoke and hot gases, or by mechanical means.

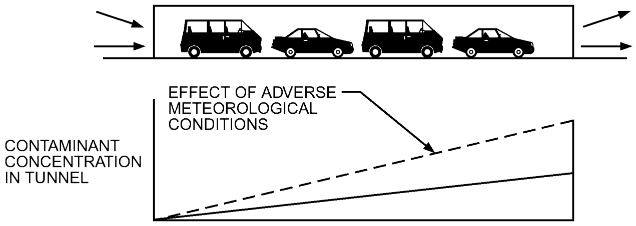
Ventilation Modes. A range of mechanical ventilation is typically considered for road tunnels: normal, congested, emergency, and temporary, as discussed in the section on Tunnel Ventilation Concepts.

Ventilation Systems. Ventilation must dilute contaminants during normal and congested tunnel operations and control smoke during emergency operations. Factors affecting ventilation system selection include tunnel length, cross section, and grade; surrounding environment; traffic volume, direction (i.e., unidirectional or bidirectional), and mix; and construction cost.

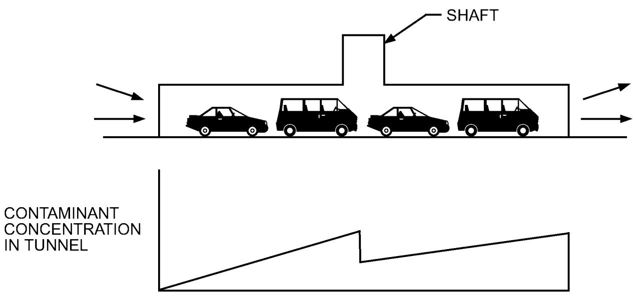
Natural and traffic-induced ventilation systems are adequate for relatively short tunnels, and for those with low traffic volume or density. Long, heavily traveled tunnels should have mechanical ventilation systems. The tunnel length at which this change takes effect is somewhere between 350 and 650 m.

Natural Ventilation. Airflow through a naturally ventilated tunnel can be portal-to-portal (Figure 2A) or portal-to-shaft (Figure 2B). Portal-to-portal flow functions best with unidirectional traffic, which produces a consistent, positive airflow. In this case, air speed in the roadway area is relatively uniform, and the contaminant concentration increases to a maximum at the exit portal. Under adverse atmospheric conditions, air speed may decrease and contaminant concentration may increase, as shown by the dashed line in Figure 2A.

Introducing bidirectional traffic into such a tunnel further reduces longitudinal airflow and increases the average contaminant concentration. The maximum contaminant level in a tunnel with bidirectional traffic will not likely occur at the portal, and will not necessarily occur at the midpoint of the tunnel.



A. PORTAL-TO-PORTAL



B. PORTAL-TO-SHAFT

Fig. 2 Natural Ventilation

A naturally ventilated tunnel with an intermediate shaft (Figure 2B) is better suited for bidirectional traffic; however, airflow through the shaft is also affected by adverse atmospheric conditions. The stack effect benefit of the shaft depends on air/rock temperatures, wind, and shaft height. Adding more than one shaft to a tunnel may be more of a disadvantage than an advantage, because a pocket of contaminated air can be trapped between the shafts.

Naturally ventilated tunnels over 300 m long require emergency ventilation to extract smoke and hot gases generated during a fire, as recommended by NFPA *Standard* 502. This standard also further recommends that tunnels between 240 and 300 m long require engineering analyses to determine the need for emergency ventilation. Emergency ventilation systems may also be used to remove stagnant contaminants during adverse atmospheric conditions. Because of the uncertainties of natural ventilation, especially the effects of adverse meteorological and operating conditions, reliance on natural ventilation to maintain carbon monoxide (CO) levels for tunnels over 240 m long should be thoroughly evaluated. This is particularly important for tunnels with anticipated heavy or congested traffic. If natural ventilation is deemed inadequate, a mechanical system should be considered for normal operations.

Smoke from a fire in a tunnel with only natural ventilation is driven primarily by the buoyant effects of hot gases and tends to flow upgrade. The steeper the grade, the faster the smoke moves, thus restricting the ability of motorists trapped between the incident and a portal at higher elevation to evacuate the tunnel safely. As shown in Table 2, the Massachusetts Highway Department and Federal Highway Administration (MHD/FHWA) (1995) demonstrated how smoke moves in a naturally ventilated tunnel.

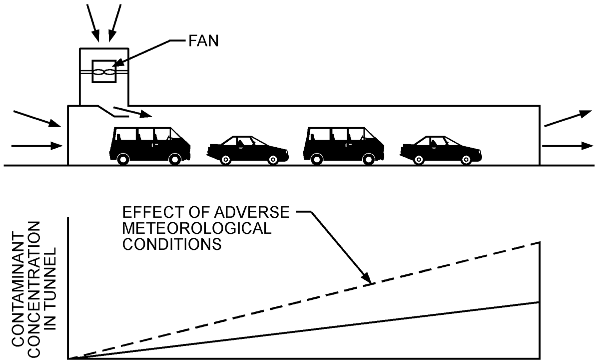
Mechanical Ventilation. A tunnel that is long, has a heavy traffic flow, or experiences frequent adverse atmospheric conditions, requires fan-based mechanical ventilation. Options include longitudinal ventilation, semitransverse ventilation, and full transverse ventilation.

Longitudinal ventilation introduces or removes air from the tunnel at a limited number of points, creating longitudinal airflow along the roadway. Longitudinal ventilation can be accomplished either by push-pull vent shafts, injection, jet fan operation, or a combination of injection and extraction at intermediate points in the tunnel. Injectors and jet fans are classified as impulse systems, because they impart a momentum to the tunnel flow, as the primary high-velocity jet diffuses out. At start-up, this thrust causes the air in the tunnel to accelerate until equilibrium is established between this force and the opposing drag forces due to viscous friction and the additional pressure losses at the tunnel portals, traffic, wind, and fire, etc.

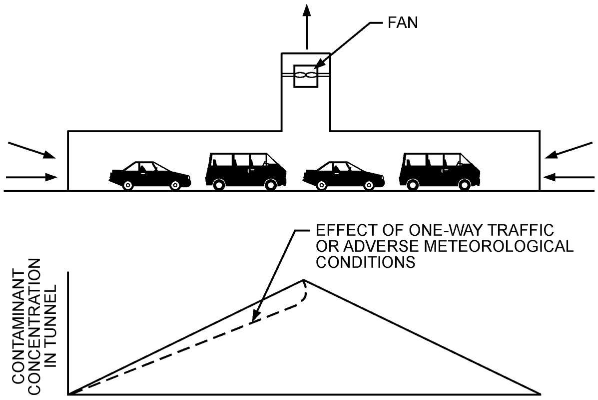
Injection longitudinal ventilation, frequently used in rail tunnels, uses externally located fans to inject air into the tunnel through a high-velocity Saccardo nozzle, as shown in Figure 3A. This air injection, usually in the direction of traffic flow, induces additional longitudinal airflow. The Saccardo nozzle functions on the principle that a high-velocity air jet injected at a small angle to the tunnel axis can induce a high-volume longitudinal airflow in the tunnel. The amount of induced flow depends primarily on the nozzle area, discharge velocity and angle of the nozzle, as well as downstream air resistances. This type of ventilation is most effective with unidirectional traffic flow.

With injection longitudinal ventilation, air speed remains uniform throughout the tunnel, and the contaminant concentration increases from zero at the entrance to a maximum at the exit. Adverse atmospheric conditions can reduce system effectiveness. The contaminant level at the exit increases as airflow decreases or tunnel length increases.

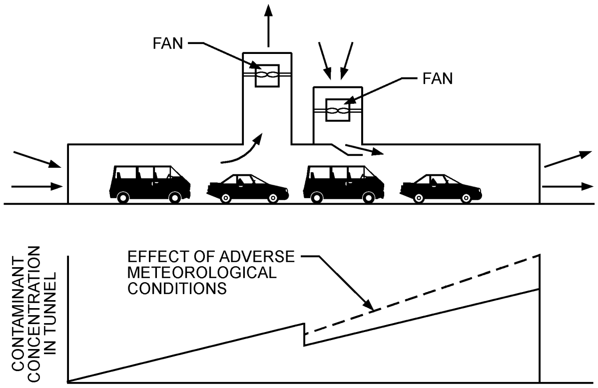
Injection longitudinal ventilation, with supply at a limited number of tunnel locations, is economical because it requires the fewest fans, places the least operating burden on fans, and requires no



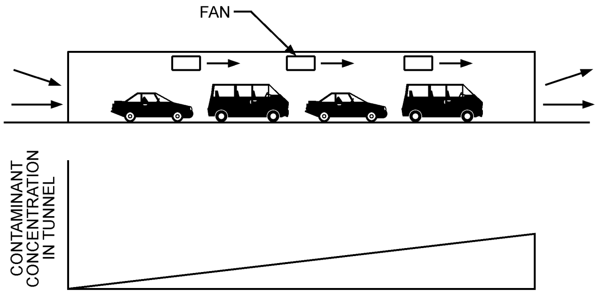
A. WITH JET INJECTION



B. WITH ONE SHAFT



C. WITH TWO SHAFTS AND JET INJECTION



D. WITH JET FANS

Fig. 3 Longitudinal Ventilation

Table 2 Smoke Movement During Natural Ventilation Tests
(Memorial Tunnel Fire Ventilation Test Program)

Test No.	Fire Heat Release Rate, MW		Smoke Layer Begins Descent, min	Smoke Fills Tunnel Roadway, min	Peak Smoke Velocity, m/s
	Nominal	Peak			
501	20	29	3+	5	6.1
502	50	57	1+	3	8.1

Note: Tunnel grade is 3.2%.

distribution air ducts. As the length of the tunnel increases, however, disadvantages become apparent, such as excessive air velocities in the roadway and smoke being drawn the entire length of the roadway during an emergency.

The main aerodynamic differences between the jet fan and Saccardo injectors are that the injectors impart thrust at one location in the tunnel, whereas in jet fan systems this thrust is distributed along the tunnel. Injectors use outdoor air as primary flow, whereas the primary airflow in jet fans enters the fan inlet from the tunnel.

Saccardo injectors may operate in a flow induction mode (low tunnel air resistance) or in flow rejection mode (high tunnel air resistance); both modes are acceptable. This means there may be flow reversal at the nozzle position with flow exiting the near portal, whereas jet fans always induce flow from one portal to the other. Flow under jet fans in a highly resistive tunnel may recirculate, but this is a strictly local feature.

A brief comparison of the technical and economic features of the two longitudinal impulse ventilation systems reveals the following:

- Jet fans have little or no civil engineering costs for installation, but have significant electrical cabling costs. Saccardo injectors require expensive civil engineering work to install the fans at the tunnel portal, with no cabling distribution costs.
- Routine maintenance or emergency repair work on jet fans usually requires disruption of normal tunnel service and availability; this is not the case for Saccardo injectors, which can be accessed externally.
- Saccardo injectors eliminate electrical cabling in the tunnel, providing a clear safety and cost advantage over jet fans.
- Jet fans take up headroom in the tunnel ceiling, which limits the effective dynamic clearance envelope of the traffic, whereas Saccardo injectors are located outdoor the tunnel, making them ideal in tightly configured tunnels.
- Saccardo injectors deliver their thrust at a single point, making them quite vulnerable to local tunnel fixtures. For example, a badly placed traffic sign, LED display, lighting equipment, or any significant blockage near the outlet of an ejector can cause a dramatic drop in ejector performance, whereas jet fans are less affected, because their thrust is distributed.
- Jet fans are also derated when operating at elevated temperatures during a fire (lower density), whereas injectors are both safely outdoor the fire's reach as well as immune to thrust reduction by virtue of using fresh air for primary intake. This makes Saccardo injectors ideal for emergency smoke clearance. The high air velocities in the path of egress should be assessed.

These relative merits are crucial at the initial concept phase, when deciding on the type of ventilation system for any particular tunnel.

A longitudinal ventilation system with one fan shaft (Figure 3B) is similar to the naturally ventilated system with a shaft, except that it provides a positive stack effect. Bidirectional traffic in a tunnel ventilated this way causes peak contaminant concentration at the shaft. For unidirectional tunnels, contaminant levels become unbalanced.

Another form of longitudinal system has two shafts near the center of the tunnel: one for exhaust and one for supply (Figure 3C). In this arrangement, part of the air flowing in the roadway is replaced by the interaction at the shafts, which reduces the concentration of contaminants in the second half of the tunnel. This concept is only effective for tunnels with unidirectional traffic flow. Adverse wind conditions can reduce tunnel airflow by short-circuiting the flow of air from the supply fan shaft/injection port to the exhaust fan/shaft, which causes contaminant concentrations to increase in the second half of the tunnel.

Construction costs of two-shaft tunnels can be reduced if a single shaft with a dividing wall is constructed. However, this significantly increases the potential for short-circuited airflows from supply shaft to exhaust shaft; under these circumstances, the separation between exhaust shaft and intake shaft should be maximized.

Jet fan longitudinal ventilation has been installed in a number of tunnels worldwide. With this scheme, specially designed axial fans (jet fans) are mounted at the tunnel ceiling (Figure 3D). This system eliminates the space needed to house ventilation fans in a separate structure or ventilation building, but may require greater tunnel height or width to accommodate the jet fans so that they are outdoor of the tunnel's dynamic clearance envelope. This envelope, formed by the vertical and horizontal planes surrounding the roadway in a tunnel, defines the maximum limits of the predicted vertical and lateral movement of vehicles traveling on the roadway at design speed. As tunnel length increases, however, disadvantages become apparent, such as excessive air speed in the roadway and smoke being drawn the entire length of the roadway during an emergency.

Longitudinal ventilation is the most effective method of smoke control in a road tunnel with unidirectional traffic. A ventilation system must generate sufficient longitudinal air velocity to prevent **backlayering** of smoke (movement of smoke and hot gases against ventilation airflow in the tunnel roadway). The air velocity necessary to prevent backlayering over stalled or blocked motor vehicles is the minimum velocity needed for smoke control in a longitudinal ventilation system and is known as the **critical velocity**.

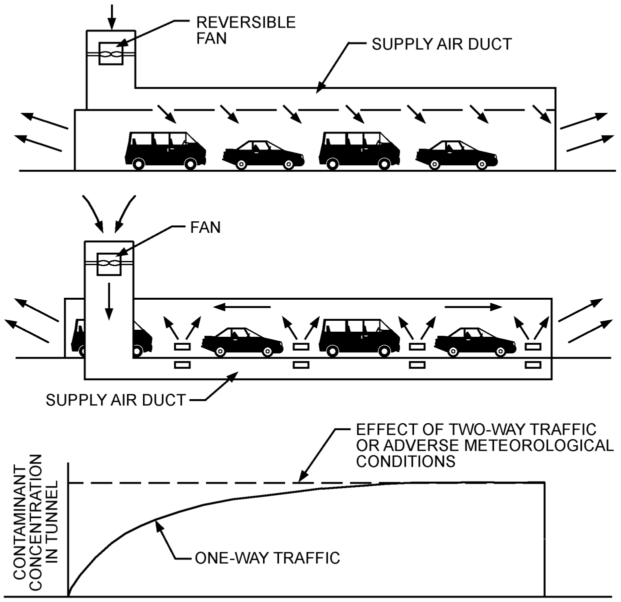
Semitransverse ventilation can be configured for supply or exhaust. This type of ventilation involves the uniform distribution (supply) or collection (exhaust) of air throughout the length of a road tunnel. Semitransverse ventilation is normally used in tunnels up to about 2000 m; beyond that length, tunnel air velocity near the portals becomes excessive.

Supply semitransverse ventilation in a tunnel with bidirectional traffic produces a uniform level of contaminants throughout, because air and vehicle exhaust gases enter the roadway area at the same uniform rate. With unidirectional traffic, additional airflow is generated by vehicle movement, thus reducing the contaminant level in the first half of the tunnel (Figure 4A).

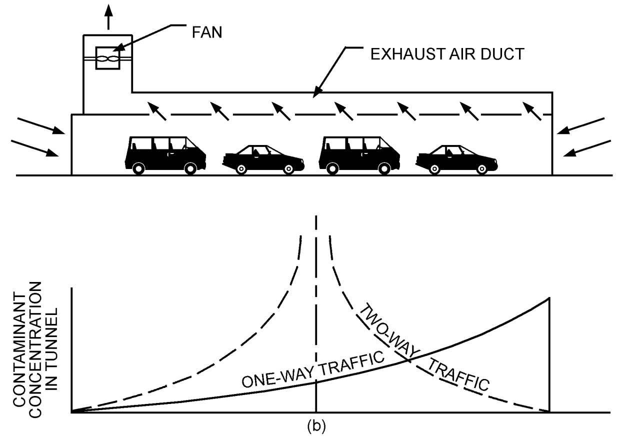
Because tunnel airflow is fan-generated, this type of ventilation is not adversely affected by atmospheric conditions. Air flows the length of the tunnel in a duct with supply outlets spaced at predetermined distances. Fresh air is best introduced at vehicle exhaust pipe level to dilute exhaust gases immediately. The pressure differential between the duct and the roadway must be enough to counteract the effects of piston action and adverse atmospheric winds.

If a fire occurs in the tunnel, the supply air initially dilutes the smoke. Supply semitransverse ventilation should be operated in reverse mode for the emergency, so that fresh air enters through the portals and creates a tenable environment for both emergency egress and firefighter ingress. Therefore, a supply semitransverse ventilation system should preferably have a ceiling supply (in spite of the disadvantage during normal operations) and reversible fans, so that smoke can be drawn up to the ceiling during a tunnel fire.

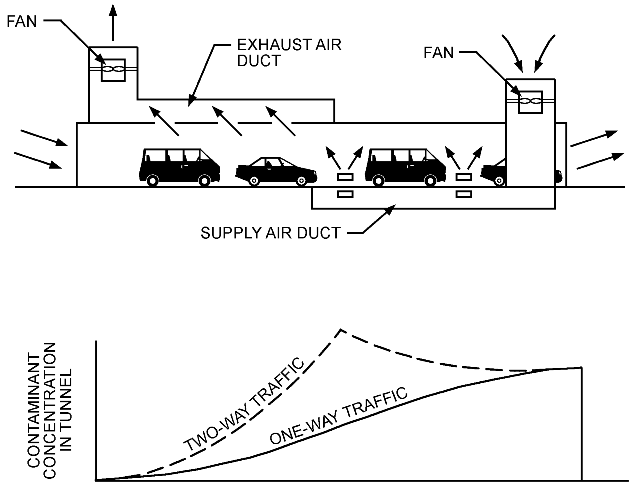
Exhaust semitransverse ventilation (Figure 4B) in a tunnel with unidirectional traffic flow produces a maximum contaminant concentration at the exit portal. In a tunnel with bidirectional traffic



A. WITH SUPPLY DUCT



B. WITH EXHAUST DUCT



C. WITH SUPPLY AND EXHAUST DUCT

Fig. 4 Semitransverse Ventilation

flow, the maximum concentration of contaminants is located near the center of the tunnel. A combination supply and exhaust semitransverse system (Figure 4C) should be applied only in a unidirectional tunnel where air entering with the traffic stream is exhausted in the first half of the tunnel, and air supplied in the second half of the tunnel is exhausted through the exit portal.

In a fire emergency, both exhaust semitransverse ventilation and (reversed) semitransverse supply create a longitudinal air velocity in the tunnel roadway, and extract smoke and hot gases at uniform intervals.

Full transverse ventilation is used in extremely long tunnels and in tunnels with heavy traffic volume. It uses both a supply and an exhaust duct system to uniformly distribute supply air and collect vitiated air throughout the tunnel length (Figure 5). Because a tunnel with full transverse ventilation is typically long and served by more than one mechanical ventilation system, it is usually configured into ventilation zones, each served by a dedicated set of supply and exhaust fans. Each zone can be operated independently of adjacent zones, so the tunnel operator can change the direction of airflow in the tunnel by varying the level of operation of the supply and exhaust fans. This feature is important during fire emergencies.

With this ventilation system arrangement in balanced operation, air pressure along the roadway is uniform and there is no longitudinal airflow except that generated by the traffic piston effect, which tends to reduce contaminant levels. The pressure differential between the ducts and the roadway must be sufficient to ensure proper air distribution under all ventilation conditions.

During a fire, exhaust fans in the full transverse system should operate at the highest available capacity, and supply fans should operate at a somewhat lower capacity. This allows the stratified smoke layer (at the tunnel ceiling) to remain at that higher elevation and be extracted by the exhaust system without mixing, and allows fresh air to enter through the portals, which creates a tenable environment for both emergency egress and firefighter ingress.

In longer tunnels, individual ventilation zones should be able to control smoke flow so that the zone with traffic trapped behind a fire is provided with maximum supply and no exhaust, and the zone on the other side of the fire (where unimpeded traffic has continued onward) is provided with maximum exhaust and minimum or no supply.

Full-scale tests conducted by Fieldner et al. (1921) showed that supply air inlets should be at vehicle exhaust pipe level, and exhaust outlets should be in the tunnel ceiling for rapid dilution of exhaust gases under nonemergency operation. Depending on the number of traffic lanes and tunnel width, airflow can be concentrated on one side, or divided over two sides.

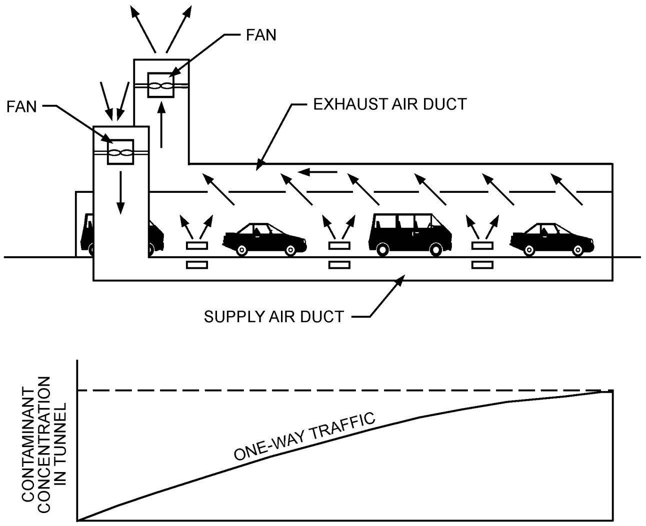


Fig. 5 Full Transverse Ventilation

Other Ventilation Systems. There are many variations and combinations of the road tunnel ventilation systems described here. Most hybrid systems are configured to solve a particular problem faced in the development and planning of a specific tunnel, such as excessive air contaminants exiting at the portal(s). Figure 6 shows a hybrid system developed for a tunnel with a near-zero level of acceptable contaminant discharge at one portal. This system is essentially a semitransverse supply system, with a semitransverse exhaust system added in section 3. The exhaust system minimizes pollutant discharge at the exit portal, which is located near extremely sensitive environmental receptors.

Ventilation System Enhancements. **Single-point extraction** is an enhancement to a transverse system that adds large openings to the extraction (or exhaust) duct. These openings include devices that can be operated during a fire emergency to extract a large volume of smoke as close to the fire source as possible. Tests proved this concept effective in reducing air temperature and smoke volume in the tunnel. The size of the duct openings tested ranged from 9.3 to 28 m^2 (MHD/FHWA 1995).

Oversized exhaust ports are simply expanded exhaust ports installed in the exhaust duct of a transverse or semitransverse ventilation system. Two methods are used to create this configuration. One is to install a damper with a fusible link; another uses a material that, when heated to a specific temperature, melts and opens the airway. Meltable materials showed only limited success in testing (MHD/FHWA 1995).

Normal Ventilation Air Quantities.

Contaminant Emission Rates. Because of the asphyxiate nature of the gas, CO is the exhaust gas constituent of greatest concern from spark-ignition engines. From compression-ignition (diesel) engines, the critical contaminants are nitrogen oxides (NO_x), such as nitric oxide (NO) and nitrogen dioxide (NO_2). Tests and operating experience indicate that, when CO level is properly diluted, other dangerous and objectionable exhaust by-products are also diluted to acceptable levels, although this trend needs reviewing with newer vehicle fleets. An exception is the large amount of unburned hydrocarbons from vehicles with diesel engines; when diesel-engine vehicles exceed 15% of the traffic mix, visibility in the tunnel can become a serious concern. In addition, suspended particles from tires and general road dust are gradually forming a larger percentage of particulate matter in the tunnel environment, and must be considered in addition to engine emissions. The section on Bus Terminals includes further information on diesel engine contaminants and their dilution.

Vehicle emissions of CO, NO_x, and hydrocarbons for any given calendar year can be predicted for cars and trucks operating in the United States by using the MOBILE models, developed and maintained by the U.S. Environmental Protection Agency. The current version is MOBILE6.2 (EPA 2002). In contaminant emission rate analyses, the following practices and assumptions may be implemented:

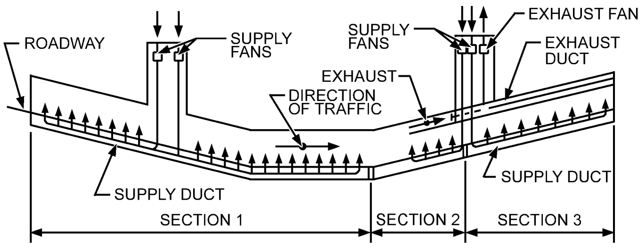


Fig. 6 Combined Ventilation System

- CO emission rates are higher during acceleration and deceleration than at constant speed; this effect may be accounted for by adding a 10% safety factor to the computations.
- The effect of positive or negative grades up to 2% is usually neglected. Engineers should use judgment, or available data, in applying correction factors for positive grades greater than 2%.
- Traffic is assumed to move as a unit, with a constant space interval between vehicles, regardless of roadway grade.
- Average passenger vehicle dimensions may be assumed where specific vehicle data are unavailable.

Table 3 presents typical physical data for automobiles for use in normal ventilation air quantity analyses.

Allowable Carbon Monoxide. EPA's (1975) supplement to its *Guidelines for Review of Environmental Impact Statements* concerns the concentration of CO in tunnels. This supplement evolved into a design approach based on keeping CO concentration at or below 143 mg/m^3 (125 ppm), for a maximum 1 h exposure time, for tunnels located at or below an altitude of 1000 m. In 1989, the EPA revised its recommendations for maximum CO levels in tunnels located at or below an altitude of 1500 m to the following:

- A maximum of 137 mg/m^3 (120 ppm) for 15 min exposure
- A maximum of 74 mg/m^3 (65 ppm) for 30 min exposure
- A maximum of 52 mg/m^3 (45 ppm) for 45 min exposure
- A maximum of 40 mg/m^3 (35 ppm) for 60 min exposure

These guidelines do not apply to tunnels in operation before the adoption date.

At higher elevations, vehicle CO emissions are greatly increased, and human tolerance to CO exposure is reduced. For tunnels above 1500 m, the engineer should consult with medical authorities to establish a proper design value for CO concentrations. Unless otherwise specified, the material in this chapter refers to tunnels at or below an altitude of 1500 m.

Outdoor air standards and regulations such as those from the Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH) are discussed in the section on Bus Terminals.

Emergency Ventilation Air Quantities. A road tunnel ventilation system must be able to protect the traveling public during the most adverse and dangerous conditions (e.g., fires), as well as during normal conditions. Establishing the requisite air volume requirements is difficult because of many uncontrollable variables, such as the possible number of vehicle combinations and traffic situations that could occur during the lifetime of the facility.

For many years, the rule of thumb has been 0.155 m^3/s per lane-metre. The Memorial Tunnel Fire Ventilation Test Program (MHD/FHWA 1995) showed that this value is, in fact, a reasonable first pass at an emergency ventilation rate for a road tunnel.

Longitudinal flow, single-point extraction, and dilution are three primary methods for controlling smoke flow in a tunnel. Both longitudinal flow and single-point extraction depend on the ability of the emergency ventilation system to generate the critical velocity necessary to prevent backlayering.

Table 3 Average Dimensional Data for Automobiles Sold in the United States

Size/Class	Wheelbase, m	Length, m	Frontal Area, m^2
Subcompact	2.4	4.3	1.6
Compact	2.7	4.8	1.8
Midsize	3.0	5.5	2.0
Large	3.0	5.6	2.1
Average	2.80	5.06	1.89

Critical Velocity. The concept of critical velocity is addressed in the section on Design Approach, under Tunnels.

Design Fire Size. The design fire size selected significantly affects the magnitude of the critical velocity needed to prevent backlayering. Table 4 provides typical fire size data for a selection of road tunnel vehicles.

Temperature. A fire in a tunnel significantly increases air temperature in the tunnel roadway and exhaust duct. Thus, both the tunnel structure and ventilation equipment are exposed to the high smoke/gas temperature. The air temperatures shown in Table 5 provide guidance in selecting design exposure temperatures for ventilation equipment.

Testing. The Memorial Tunnel Fire Ventilation Test Program was a full-scale test program conducted to evaluate the effectiveness of various tunnel ventilation systems and ventilation airflow rates to control smoke from a fire (MHD/FHWA 1995). The results are useful in developing both emergency tunnel ventilation systems and emergency operational procedures.

Pressure Evaluation. Air pressure losses in tunnel ducts must be evaluated to compute the fan pressure and drive requirements. Fan selection should be based on total pressure across the fans, not on static pressure alone.

Fan total pressure (FTP) is defined by ASHRAE *Standard* 51/AMCA *Standard* 210 as the algebraic difference between the total pressures at fan discharge (TP_2) and fan inlet (TP_1), as shown in Figure 7. The fan velocity pressure (FVP) is defined as the pressure (VP_2) corresponding to the bulk air velocity and air density at the fan discharge:

$$FVP = VP_2 \tag{3}$$

Fan static pressure (FSP) is equal to the difference between fan total pressure and the fan velocity pressure:

$$FSP = FTP - FVP \tag{4}$$

Table 4 Typical Fire Size Data for Road Vehicles

Cause of Fire	Peak Fire Heat Release Rate, MW
Passenger car	5 to 10
Multiple passenger cars (2 to 4 Vehicles)	10 to 20
Bus	20 to 30
Heavy goods truck	70 to 200
Tanker[3]	200 to 300

Source: NFPA *Standard* 502 (2008).
Notes:
1. The designer should consider rate of fire development peak heat release rates may be reached within 10 min), number of vehicles that could be involved in fire, and potential for fire to spread from one vehicle to another.
2. Temperatures directly above fire can be expected to be as high as 1000 to 1400°C.
3. Flammable and combustible liquids for tanker fire design should include adequate drainage to limit area of pool fire and its duration. Heat release rate may be greater than listed if more than one vehicle is involved.

Table 5 Maximum Air Temperatures at Ventilation Fans During Memorial Tunnel Fire Ventilation Test Program

Nominal FHRR, MW	Temperature at Central Fans,[a] °C	Temperature at Jet Fans,[b] °C
20	107	232
50	124	371
100	163	677

Source: MHD/FHWA (1995)
FHRR = Fire heat release rate
[a] Central fans located 213 m from fire site.
[b] Jet fans located 52 m downstream of fire site.

TP_2 must equal total pressure losses $\Delta TP_{2\text{-}3}$ in the discharge duct and exit pressure TP_3. Static pressure at the exit SP_3 is equal to zero.

$$TP_2 = \Delta TP_{2\text{-}3} + TP_3 = \Delta TP_{2\text{-}3} + VP_3 \qquad (5)$$

Likewise, total pressure at fan inlet TP_1 must equal the total pressure losses in the inlet duct and the inlet pressure:

$$TP_1 = TP_0 + \Delta TP_{0\text{-}1} \qquad (6)$$

Straight Ducts. Straight ducts in tunnel ventilation systems either (1) transport air or (2) uniformly distribute (supply) or collect (exhaust) air. Several methods have been developed to predict pressure losses in a duct of constant cross-sectional area that uniformly distributes or collects air. The most widely used method was developed for the Holland Tunnel in New York (Singstad 1929). The following relationships, based on Singstad's work, give pressure losses at any point in a duct.

Total pressure for a **supply duct**

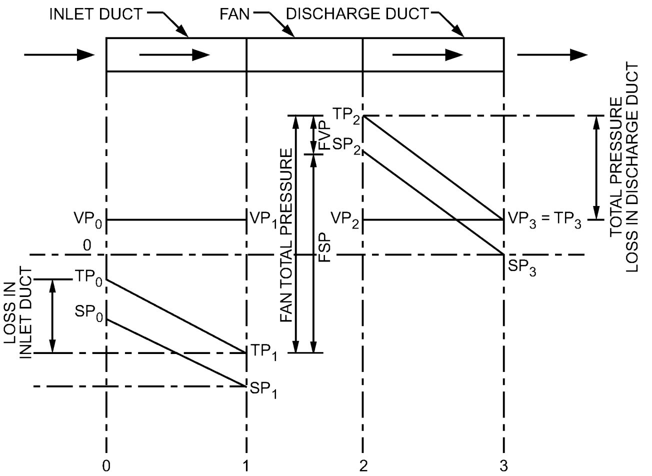
$$P_T = P_1 + \left(\frac{\rho_a}{g_c}\right)\left\{\frac{V_o^2}{2}\left[\frac{\alpha L Z^3}{3H} - (1-K)\frac{Z^2}{2}\right] + \frac{\beta L Z}{2H^3}\right\} \qquad (7)$$

Static pressure loss for an **exhaust duct**

$$P_S = P_1 + \left(\frac{\rho_a}{g_c}\right)\left\{\frac{V_o^2}{2}\left[\frac{\alpha L Z^3}{(3+c)H} + \frac{3Z^2}{(2+c)}\right] + \frac{\beta L Z}{2H^3(1+c)}\right\} \qquad (8)$$

where

P_T = total pressure loss at any point in duct, Pa
P_S = static pressure loss at any point in duct, Pa
P_1 = pressure at last outlet, Pa
ρ_a = density of air, kg/m^3
V_o = velocity of air entering duct, m/s
L = total length of duct, m
X = distance from duct entrance to any location, m
$Z = (L - X)/L$
H = hydraulic radius, m
K = constant accounting for turbulence = 0.615
α = constant related to coefficient of friction for concrete = 0.0035
β = constant related to coefficient of friction for concrete = 0.00012 m^4/s^2
c = constant relating to turbulence of exhaust port
= 0.20 for exhaust rates less than 0.31 m^3/s per metre
= 0.25 for exhaust rates greater than 0.31 m^3/s per metre
g_c = gravitational constant = 1.0 (m·kg)/(N·s^2)



$FTP = TP_1 - TP_2$
$FSP = FTP - FVP = SP_2 - TP_1$

Fig. 7 Fan Total Pressure

The geometry of the exhaust air slot connection to the main duct is a concern in deriving the exhaust duct equation. The derivation is based on a 45° angle between the slot discharge and the main airstream axes. Variations in this angle can greatly affect the energy losses at the convergence from each exhaust slot, with total pressure losses for a 90° connection increasing by 50 to 100% over those associated with 45° angles (Haerter 1963).

For **distribution ducts** with sections that differ along their length, these equations may also be solved sequentially for each constant-area section, with transition losses considered at each change in section area. For a **transport duct** with constant cross-sectional area and constant air velocity, pressure losses are due to friction alone and can be computed using the standard expressions for losses in ducts and fittings (see Chapter 21 of the 2013 *ASHRAE Handbook—Fundamentals*).

Carbon Monoxide Analyzers and Recorders. Air quality in a tunnel should be monitored continuously at several key points. CO is the contaminant usually selected as the prime indicator of tunnel air quality, although in some of the more recent European road tunnels, NO_x and visibility levels are now the main indicators driving the ventilation requirements, perhaps because of the prominence of diesel cars. CO-analyzing instruments base their measurements on one of the following three processes:

- **Catalytic oxidation (metal oxide)** analysis offers reliability and stability at a moderate initial cost. Maintenance requirements are low, plus these instruments can be calibrated and serviced by maintenance personnel after only brief instruction.
- **Infrared** analysis is sensitive and responsive, but has a high initial cost. This instrument is precise but complex, and requires a highly trained technician for maintenance and servicing.
- **Electrochemical** analysis is precise; the units are compact, lightweight, and moderately priced, but they have a limited life (usually not exceeding two years) and thus require periodic replacement.

As shown in Figures 1 to 4, the location of the peak emission concentration level in a road tunnel is a function of both traffic operation (unidirectional versus bidirectional) and type of ventilation provided (natural, longitudinal, semitransverse, or full transverse). Generally, time-averaged CO concentrations for the full length of the tunnel are needed to determine appropriate ventilation rates and/or required regulatory reporting. Time-averaged concentrations are particularly important in road tunnels where the ventilation system control is integrated with the CO monitoring system.

CO sampling locations in a road tunnel should be selected carefully to ensure meaningful results. For example, samples taken too close to an entry or exit portal do not accurately represent the overall level that can be expected throughout the tunnel. Multiple sampling locations are recommended to ensure that a reasonable average is reported. Multiple analyzers are also recommended to provide a reasonable level of redundancy in case of analyzer failure or loss of calibration. In longer road tunnels, which may have multiple, independently operated ventilation zones, the selected sampling locations should provide a representative CO concentration level for each ventilation zone. Strip chart recorders and microprocessors are commonly used to keep a permanent record of road tunnel CO levels.

CO analyzers and their probes should not be located directly in a roadway tunnel or in its exhaust plenum. Instead, an air pump should draw samples from the tunnel/exhaust duct through a sample line to the CO analyzer. This configuration eliminates the possibility of in-tunnel air velocities adversely affecting the instrument's accuracy. The length of piping between sampling point and CO analyzer should be as short as possible to maintain a reasonable air sample transport time.

Haze or smoke detectors have been used on a limited scale, but most of these instruments are optical devices and require frequent or constant cleaning with a compressed air jet. If traffic is predominantly diesel-powered, smoke haze and NO_x gases require individual monitoring in addition to that provided for CO.

Local regulations should be reviewed to determine whether ventilation exhaust monitoring is required for a particular road tunnel. If so, for tunnels using full transverse ventilation systems, CO and NO_2 pollutant sampling points should be placed carefully within the exhaust stacks/plenums. For longitudinally ventilated tunnels, sampling points should be located at least 30 m in from the exit portal.

Controls.

Centralized Control. To expedite emergency response and to reduce the number of operating personnel for a given tunnel, all ventilating equipment should be controlled at a central location. New tunnels are typically provided with computer-based control systems, which function from operational control centers. In some older tunnel facilities, fan operation is manually controlled by an operator at a central control board. The control structure for newer road tunnel ventilation systems is typically supervisory control and data acquisition (SCADA), with programmable logic controllers (PLCs) providing direct control hardware over the associated electrical equipment. The operational control center varies from one stand-alone PC (with SCADA software providing dedicated ventilation control), to redundant client/server configurations providing an integrated control system and real-time database and alarm systems for tunnel operations (Buraczynski 1997). Communication links are required between the supervisory SCADA and PLCs.

The SCADA system operator controls the ventilation equipment through a graphical user interface, developed as part of the ventilation system design. Preprogrammed responses allow the operator to select the appropriate ventilation plan or incident response mode.

The SCADA system allows the operator to view equipment status, trend data values, log data, and use an alarm system. Whereas older tunnel facilities used chart recorders for each sampling point to demonstrate that the tunnel was sufficiently ventilated and compliant with environmental air quality standards, new tunnels use SCADA to log CO levels directly onto a nonvolatile medium, such as a CD-ROM.

Emergency response functions for road tunnel ventilation require that control system design meets life safety system standards. A high-availability system is required to respond on demand to fire incidents. High availability is obtained by using high-quality industrial components, and by adding built-in redundancy. The design must protect the system against common event failures; therefore, redundant communication links are segregated and physically routed in separate raceways. High-integrity software for both the PLCs and the SCADA system is another major consideration.

Once a supervisory command is received, the PLC control handles equipment sequencing (e.g., fan and damper start-up sequence), least-hours-run algorithms, staggered starting of fans, and all interlocks. The PLC also receives instrumentation data from the fan and fan motor, and can directly shut down the fan if needed (e.g., because of high vibration). Conditions such as high vibration and high temperature are tolerated during emergency operation.

CO-Based Control. When input to the PLC, recorded tunnel air quality data allow fan control algorithms to be run automatically. The PLC controls fans during periods of rising and falling CO levels. Fan operations are usually based on the highest level recorded from several analyzers. Spurious high levels can occur at sampling points; the PLC control algorithm prevents the ventilation system from responding to short-lived high or low levels. PLC control also simplifies hardwired systems in older tunnel facilities, and increases flexibility through program changes.

Timed Control. This automatic fan control system is best suited for installations that experience heavy rush-hour traffic. With timed control, the fan operation schedule is programmed to increase the ventilation level, in preset increments, before the anticipated traffic increase; it can also be programmed for weekend and public holiday conditions. The timed control system is relatively simple and is easily revised to suit changing traffic patterns. Because it anticipates an increased airflow requirement, the associated ventilation system can be made to respond slowly and thus avoid expensive demand charges from the local utility company. One variation of timed control is to schedule the minimum anticipated number of fans to run, and to start additional fans if high CO levels are experienced. As with the CO-based control system, a manual override is needed to cope with unanticipated conditions.

Traffic-Actuated Control. Several automatic fan control systems have been based on the recorded flow of traffic. Most require installation of computers and other electronic equipment needing specific maintenance expertise.

Local Fan Control. Local control panels are typically provided for back-up emergency ventilation control and for maintenance/servicing requirements. The local panels are often hardwired to the fan starters to make them independent from the normal SCADA/PLC control system. Protocols for handing over fan control from the SCADA/ PLC system to the local panel must also be established, so that fans do not receive conflicting operational signals during an emergency.

Rapid Transit Tunnels and Stations

Modern high-performance, air-conditioned subway vehicles consume most of the energy required to operate rapid transit and are the greatest source of heat in the underground areas of a transit system. An environmental control system (ECS) is intended to maintain reasonable comfort during normal train operations and help keep passengers safe during a fire emergency. Minimizing traction power consumption and vehicle combustible contents reduces ventilation requirements. The large amount of heat produced by rolling stock, if not properly controlled, can cause passenger discomfort, shorten equipment life, and increase maintenance requirements. Tropical climates present additional concerns for underground rail transit systems and make environment control more critical.

Temperature, humidity, air velocity, air pressure change, and rate of air pressure change help determine ECS performance. These conditions are affected by time of day (i.e., morning peak, evening peak, or off-peak), circumstance (i.e., normal, congested, or emergency operations), and location in the system (i.e., tunnel, station platform, entrance, or stairway). The *Subway Environmental Design Handbook* (SEDH) (DOT 1976) provides comprehensive and authoritative design aids on ECS performance; information in the SEDH is based on design experience, validated by field and model testing.

Normal operations involve trains moving through the subway system and stopping at stations according to schedule, and passengers traveling smoothly through stations to and from transit vehicles. The piston action of moving trains is the chief means of providing ventilation and maintaining an acceptable environment (i.e., air velocity and temperature) in the tunnels. Because normal operations are predominant, considerable effort should be made to optimize ECS performance during this mode.

One concern is limiting the air velocity caused by approaching trains on passengers waiting on the platform. Piston-induced platform air velocities can be reduced by providing a pressure relief shaft (also known as a blast shaft) at each end of affected platforms.

During normal train operations, platform passenger comfort is a function of the temperature and humidity of ambient and station air, platform air velocity, and duration of exposure to the station environment. For example, a person entering a 29°C station from 32°C outdoor conditions will momentarily feel more comfortable, particularly after a fast-paced walk ending with total rest, even if standing. However, in a short time, usually about 6 min, the person's metabolism adjusts to the new environment and produces a similar level of comfort as before. If a train were to arrive during this period, a relatively high station air temperature would be acceptable. Traditionally, the relative warmth index (RWI) has quantified this transient effect, allowing the designer to select an appropriate design air temperature for the station based on the transient, rather than steady-state, sensation of comfort. More recently, new transient thermal comfort models have been developed, leading to more advanced comfort indices being proposed (Gilbey 2006; Guan et al. 2009). Design temperatures based on the transient approach are typically higher (often 3 to 5 K) than those selected by the steady-state approach, and hence result in reduced cooling load and air-conditioning system requirements.

Congested operations result from delays or operational problems that prevent the normal dispatch of trains, such as missed headways or low-speed train operations. Trains may wait in stations, or stop at predetermined locations in tunnels during congested operations. Delays usually range from 30 s to 20 min, although longer delays may occasionally be experienced. Passenger evacuations or endangerment are not expected to occur. Congested ventilation analyses should focus on the potential need for forced (mechanical) ventilation, which may be required to control tunnel air temperatures in support of continued operation of train air-conditioning units. The aim of forced ventilation is to maintain onboard passenger comfort during congestion by operating the vehicle air conditioning system to prevent passengers from evacuating the train.

Emergency operations occur as a result of a fire in a subway tunnel or station. Fire emergencies include trash fires, track electrical fires, train electrical fires, and acts of arson. Some fires may involve entire train cars. Station fires are mostly trashcan fires. Statistically, most fire incidents reported in mass transit systems (up to 99%) are small and low in smoke generation; these fires typically cause only minor injuries and operational disturbances. The most serious emergency condition is a fire on a stopped train in a tunnel; this event disrupts traffic and requires passenger evacuation. For this case, adequate tunnel ventilation is required to control smoke flow and enable safe passenger evacuation and safe ingress of emergency response personnel. Though rare, tunnel fires must be considered because of their potential life-safety ramifications.

Design Concepts. Elements of underground rail transit ventilation design may be divided into four interrelated categories: natural, mechanical, and emergency ventilation; and station air conditioning.

Natural Ventilation. Natural ventilation (e.g., ambient air infiltration and exfiltration) in subway systems primarily results from trains moving in tightly fitting tunnels, where air generally moves in the direction of train travel. The positive air pressure generated in front of a moving train expels warm air from the subway through tunnel portals, pressure relief shafts, station entrances, and other openings; the negative pressure in the wake induces airflow into the subway through these same openings.

Considerable short-circuiting of airflow occurs in subways when two trains, traveling in opposite directions, pass each other; especially in stations or tunnels with porous walls (those with intermittent openings to allow air passage between trackways). Short-circuiting can also occur in stations and tunnels with nonporous walls where alternative airflow paths (e.g., open bypasses, cross-passageways, adits, crossovers) exist between the trackways. This short-circuited airflow reduces the net ventilation rate and increases air velocities on platforms and in entrances. During peak operating periods and high ambient temperatures, short-circuited airflow can cause undesirable heat build-up in the station.

To counter the negative effects of short-circuiting airflow, ventilation shafts are customarily located near interfaces between tunnels and stations. Shafts in station approach tunnels are often called blast shafts, because part of the tunnel air pushed by an approaching train is expelled through them before it affects the station environment. Shafts in station departure tunnels are known as relief shafts, because they relieve the negative air pressure created by departing trains. Relief shafts also induce outdoor airflow through the shaft, rather than through station entrances.

Additional shafts may be provided for natural ventilation between stations (or between portals, for underwater crossings), as dictated by tunnel length. The high cost of such ventilation structures necessitates a design that optimizes effectiveness and efficiency. Internal resistance from offsets and bends in the ventilation shaft should be kept to a minimum; shaft cross-sectional area should approximately equal the cross-sectional area of a single-track tunnel (DOT 1976).

Mechanical Ventilation. Mechanical ventilation in subways (1) supplements the natural ventilation effects of moving trains, (2) expels warm air from the system, (3) introduces fresh outdoor air, (4) supplies makeup air for exhaust, (5) restores the cooling potential of the tunnel heat sink by extracting heat stored during off hours or system shutdown, (6) reduces airflow between the tunnel and station, (7) provides outdoor air for passengers in stations or tunnels during an emergency or other unscheduled interruptions of traffic, and (8) purges smoke from the system during a fire, protecting the passengers' evacuation.

The most cost-effective design for a mechanical ventilation system serves multiple purposes. For example, a vent shaft designed for natural ventilation may also be used for emergency ventilation if a fan is installed in parallel, as part of a bypass (Figure 8). Current safety standards require emergency fans to be reversible (NFPA *Standard* 130).

Several ventilation shafts and fan plants may be required to work together to achieve many, if not all, of the eight design objectives. Depending on the shaft location, design, and local train operating characteristics, a shaft with an open bypass damper and a closed fan damper may serve as a blast or relief shaft. With the fan damper open and the bypass damper closed, air can be mechanically supplied to or exhausted from the tunnel, depending on fan rotation direction. Except for emergency ventilation, fan rotation direction is usually predetermined for various operating modes.

If a station is not air conditioned, warm air in the subway should be exchanged, at the maximum rate possible, with cooler outdoor

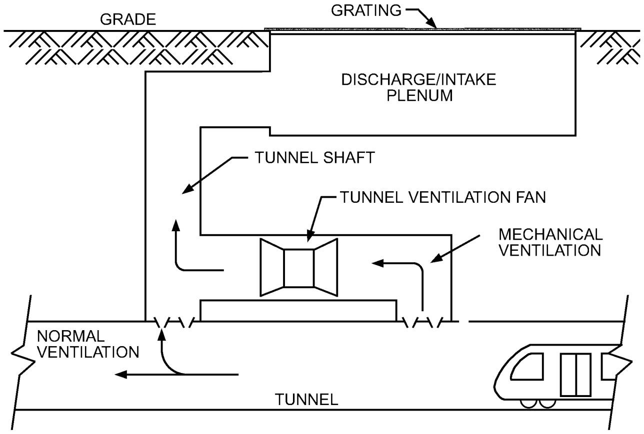


Fig. 8 Tunnel Ventilation Shaft

air. If a station is air conditioned below the ambient temperature, inflow of warmer outdoor air should be limited and controlled.

Figure 9 shows a typical tunnel ventilation system between two subway stations. Here, flow of warm tunnel air into the station is minimized by either normal or mechanical ventilation effects. In Figure 9A, air pushed ahead of the train on track 2 diverts partially to the bypass ventilation shaft and partially into the wake of a train on track 1, as a result of pressure differences. Figure 9B shows an alternative operation with the same ventilation system where mid-tunnel fans operate in exhaust mode; when outdoor air conditions are favorable, makeup air is introduced through the bypass ventilation shafts. This alternative can also either provide or supplement station ventilation. To achieve this, the bypass shafts are closed, and makeup air for the mid-tunnel exhaust fans enters through station entrances.

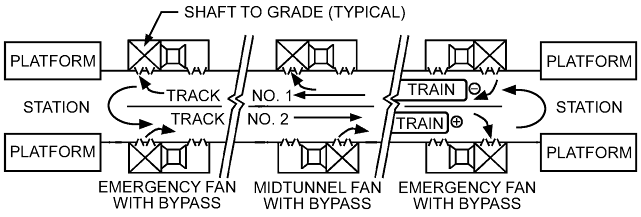
For forced air flow blown under car brake resistor grids, a more direct mechanical ventilation system (Figure 10) can be designed to remove station heat at its primary source, the underside of the train. Field tests have shown that trackway ventilation systems not only reduce upwelling of warm air into the platform areas, but also remove significant portions of heat generated by other undercar sources, such as dynamic-braking resistor grids and, in some cases, air-conditioning condenser units (DOT 1976), as long as consistent and steady air movement can be maintained from the heat source towards the exhaust grille. Ideally, makeup air for trackway exhaust should be introduced at track level, as in Figure 10A, to provide positive control over the direction of airflow; however, obstructions in the vehicle undercarriage area must be avoided when planning underplatform exhaust port and makeup air supply locations.

A more direct mechanical ventilation system (Figure 10) can be designed to remove station heat at its primary source, the underside of the train. Field tests have shown that trackway ventilation systems not only reduce upwelling of warm air into the platform areas, but also remove significant portions of heat generated by other undercar sources, such as dynamic-braking resistor grids and, in some cases, air-conditioning condenser units (DOT 1976). Ideally, makeup air for trackway exhaust should be introduced at track level, as in Figure 10A, to provide positive control over the direction of airflow; however, obstructions in the vehicle undercarriage area must be avoided when planning underplatform exhaust port and makeup air supply locations.

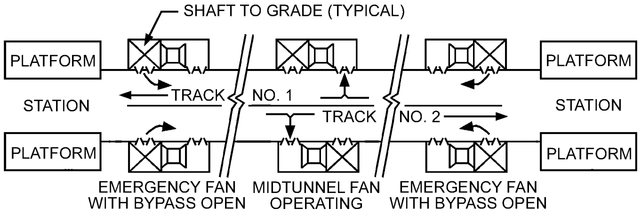
A trackway ventilation system without a dedicated makeup air supply (Figure 10B), also known as an underplatform exhaust (UPE) system, is the least effective alternative for heat removal. General design experience shows that where UPE grilles cannot be placed in close proximity to the source of undercar heat because of space constraints, or when a steady airflow cannot be established over the heat source towards the UPE grilles, heated undercar air can escape up through the gap between the car and platform edge, and the UPE effectiveness is reduced (Tabarra and Guan 2009). With a UPE system, a quantity of air equal to that withdrawn by the underplatform exhaust enters the station control volume, either from the outdoors or from the tunnels. When the ambient, or tunnel, air temperature is higher than the station design air temperature, a UPE system reduces station heat load by removing undercar heat, but it also increases station heat load by drawing in warmer air, which may affect platform passenger comfort. Because of these drawbacks, the effectiveness of a UPE system should be carefully considered and if possible modeled early, before the station design advances too far.

Figure 10C shows a cost-effective compromise: makeup air is introduced from the ceiling above the platform. Although heat removal effectiveness of this system may be less than that of the system with track-level makeup air, the inflow of warm tunnel air that may occur in a system without makeup air supply is negated.

Newer vehicles have air-conditioning grids above, generating heat near the ceiling during dwell time in the station. To exhaust this heat, an overtrack exhaust (OTE) system should be provided. OTE may be appropriate to remove fire smoke and heat. If analysis indicates that acceptable environmental conditions are achieved with OTE under normal and emergency conditions, the designer may consider evaluating the efficiency of the UPE system. The relative geometries of heat sources must be verified early in the design cycle, to enable the designer to make an informed decision.

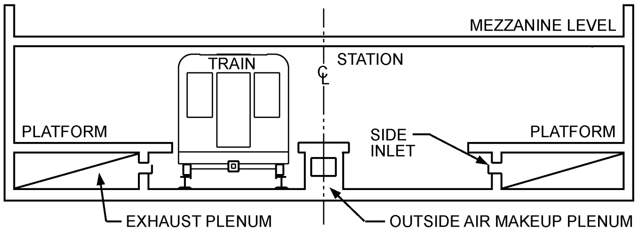


A. NORMAL VENTILATION BETWEEN STATIONS

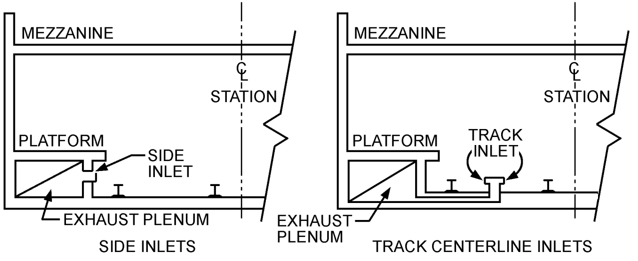


B. MECHANICAL VENTILATION BETWEEN STATIONS

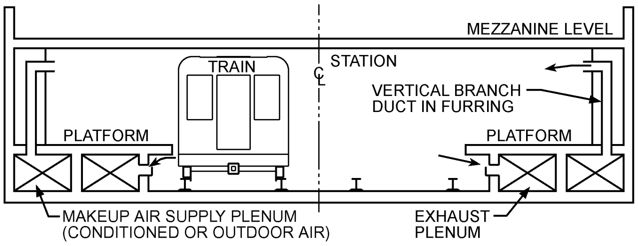
Fig. 9 Tunnel Ventilation Concept



A. OUTDOOR AIR MAKEUP AT TRACK LEVEL



B. NO MAKEUP AIR SUPPLY



C. MAKEUP AIR SUPPLY AT CEILING LEVEL

Fig. 10 Trackway Ventilation Concept (Cross-Sections)

Emergency Ventilation. During a subway tunnel fire, mechanical ventilation is an important part of the response and smoke control strategy. Within subway systems or other enclosed trainways, an emergency ventilation system is necessary to control the direction of smoke migration and allow safe evacuation of passengers and access by firefighters (see NFPA *Standard* 130). Depending on vehicle configuration, ventilation fan sizes, and tunnel geometry, emergency ventilation has the potential to affect fire size and smoke generation.

The most common method of ventilating a tunnel during a fire is push-pull fan operation: fans on one side of the fire operate in supply mode, while fans on the opposite side operate in exhaust mode. Emergency ventilation analyses should focus on determining the airflow required to preserve tenable conditions in a single evacuation path from the train. The criterion used to design emergency ventilation for underground transit systems is critical velocity, similar to that presented in the section on Road Tunnels. The presence of nonincident trains should be considered in planning the emergency ventilation system response to specific fire incidents.

Emergency ventilation system design must allow for the unpredictable location of both the disabled train and the fire source. Therefore, emergency ventilation fans should have full reverse-flow capability, so that fans on either side of a disabled train can operate together to control airflow direction and counteract undesired smoke migration.

When a disabled train is stopped between two stations and fire or smoke is discovered, outdoor air is supplied by the emergency ventilation fans at the nearest station, and smoke-laden air is exhausted past the opposite end of the train by emergency ventilation fans at the next station, unless the location of the fire dictates otherwise. Passengers can then be evacuated along the tunnel walkways via the shortest possible route (Figure 11).

Emergency ventilation analysis should consider the possibility of nonincident trains stopped behind the disabled train. In this case, emergency fans should be operated so that nonincident trains are kept in the fresh airstream; if possible, they may be used to evacuate incident-train passengers. For long subway tunnels, in particular, analysis should also consider evacuating passengers to a nonincident trackway (through cross passageways), where a dedicated rescue train can move them to safety. Emergency ventilation analyses should identify passenger evacuation/firefighter ingress routes for evaluated scenarios, and fan modes to preserve tenable conditions in those routes.

When a train fire is discovered, the train should be moved if possible to the next station, to make passenger evacuation and fire suppression easier. Emergency management plans must include provisions to (1) quickly assess any fire or smoke event, (2) communicate the situation to an operations control center, (3) establish the location of the incident train, (4) establish the general location of the fire, (5) determine the best passenger evacuation route, and (6) quickly activate emergency ventilation fans to establish smoke flow control.

Midtunnel and station trackway (OTE) ventilation fans may be used to enhance emergency ventilation; therefore, these fans must also operate under high temperatures and have reverse-flow capability.

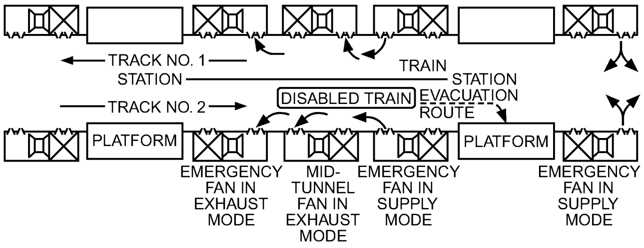


Fig. 11 Emergency Ventilation Concept

The possibility of a fire on the station platform or in another public area should also be considered. These fires are generally created by rubbish or wastepaper and are thus much smaller than train fires. However, small station fires can generate considerable smoke and create panic among passengers. Therefore, stations should be equipped with efficient fire suppression and smoke extraction systems. Stations with platform-edge doors should have fire suppression and smoke extraction systems designed specifically for that configuration.

The fire heat release rate is an important parameter in subway emergency ventilation system design. The fire heat release rate for each vehicle type depends on initiation fire, combustibility of interior materials, size of the compartment, and ventilation (door and window openings), and thus must be established individually (see the Design Fires section for more information). Typical fire size data for single transit vehicles are as follows:

- Older transit vehicle ≈ 14.7 MW
- New, hardened vehicle ≈ 10.3 MW
- Light rail vehicle ≈ 8.8 MW

Smoke obscuration is a key factor in defining a tenable environment for passenger evacuation, and visibility is often the governing criterion for station design. The smoke release rate should be calculated following acceptable procedures [e.g., Society of Fire Protection Engineers (SFPE) 2008].

Station Air Conditioning. Faster station approach speeds and closer headways, both made possible by computerized train control, have increased heat gains in subway stations. The net internal sensible heat gain for a typical two-track subway station, with 40 trains per hour per track traveling at a top speed of 80 km/h, may reach 1.5 MW, even after some tunnel heat is removed by the heat sink, station underplatform exhaust system, or tunnel ventilation system. To remove this heat from a station with a ventilation system using outdoor air and a maximum air temperature increase of 1.7 K, for example, would require roughly 660 m^3/s of outdoor air. This would be costly, and air velocities on the platforms would be objectionable to passengers.

The same amount of sensible heat gain, plus the latent heat and outdoor air loads (based on a station design air temperature 4 K lower than ambient), could be handled by about 2.2 MW of refrigeration. Even if station air conditioning is more expensive at the outset, long-term benefits include (1) reduced design airflow rates, (2) reduced ventilation shaft/duct sizing, (3) improved passenger comfort, (4) increased service life of other station equipment (e.g., escalators, elevators, fare collection), (5) reduced maintenance requirements for station equipment and structures, and (6) increased acceptance of the subway as a viable means of public transportation. Air conditioning should also be considered for other station ancillary areas, such as concourse levels and transfer levels. However, unless these walk-through areas are designed to attract patronage to concessions, the cost of air conditioning is usually not warranted.

The physical configuration of the station platform level usually determines the cooling distribution pattern. Platform areas with high ceilings, local warm spots created by trains, high-density passenger accumulation, or high-level lighting may need spot cooling. Conversely, where the train length equals platform length and the ceiling height above the platform is limited to 3 to 3.5 m, isolating heat sources and using spot cooling are usually not feasible.

In air-conditioned stations, when the enthalpy of outdoor air is higher than the station air, station air recirculation may be more economical. Thus, the station cooling system should have the flexibility of reducing the volume of outdoor air in favor of station air, based on suitably located temperature and humidity sensors. Provision for dedicated return air ducts from platforms or concourse areas with accessible filters should be considered early in station cooling design.

Air conditioning is more attractive and efficient for stations with platform-edge doors, which limit air exchange between platform and tunnels. In tropical climates, separate ventilation systems are typically used to minimize station air exfiltration and tunnel air infiltration through platform-edge doors.

Space use in a station structure for air-distribution systems is of prime concern because of the high cost of underground construction. Overhead distribution ductwork could add to the depth of excavation during subway construction. The space beneath a subway station platform is normally an excellent area for low-cost distribution of supply, return, and/or exhaust air.

Design Method. Subways typically have two discrete sets of environmental criteria: one for normal and congested train operations and one for emergency fire/smoke operations. Criteria for normal operations include limits on tunnel air temperature (through tunnel ventilation or tunnel cooling) and humidity for various times of the year, minimum ventilation rates to dilute contaminants generated in the subway, and limits on the air velocity and rate of air pressure change to which passengers may be exposed. Some of these criteria are subjective and may vary based on demographics. Criteria for emergency operations include a minimum purge time to remove smoke from a subway, critical air velocity for smoke flow control during a tunnel fire, and minimum and maximum fan-induced tunnel air velocities.

Given a set of criteria, outdoor design conditions, and appropriate tools for estimating interior heat loads, heat sink effect, ventilation requirements, tunnel air velocity, and rate of air pressure changes, design engineers can select components for the environmental control system (ECS). ECS design should consider controls for tunnel air temperature, velocity, and quality, and the air pressure change rate. Systems selected generally combine natural and mechanical ventilation, overtrack and underplatform exhaust, and station air conditioning.

Train propulsion/braking systems and configuration of the tunnels and stations greatly affect the subway environment. Therefore, the ECS must often be considered during the early stages of subway system design. Factors affecting a subway environmental control system are discussed in this section. The *Subway Environmental Design Handbook* (SEDH) (DOT 1976) and NFPA *Standard* 130 have additional information.

Analytical Data. ECS design should be based on all the parameters affecting its operation, including ambient air conditions, train operating characteristics, applicable ventilation methods, new or existing ventilation structures, and calculated heat loads. ECS efficiency should be addressed early during transit system design. The tunnel ventilation system should be integrated with the design of other tunnel systems (including power, signaling, communications, and fire/life safety systems) and with the station ventilation system design. The ECS design must satisfy the project design criteria and comply with applicable local and national (or international) codes, standards, and regulations.

The ventilation engineer should be familiar with these requirements and apply suitable design techniques, such as computer modeling and simulations (using verified/validated engineering software).

Comfort Criteria. Because passenger exposure to the subway environment is transient, comfort criteria are not as strict as those for continuous occupancy. As a general principle, the station environment should provide a smooth transition between outdoor air conditions and thermal conditions in the transit vehicles. Except where platform edge doors are installed, train movement usually generates desirable air movement in stations, but air velocity should not exceed 5 m/s in public areas during normal train operations.

Air Quality. Air quality in a subway system is influenced by many factors, some of which are not under the direct control of the HVAC engineer. Some particulates, gaseous contaminants, and odorants in the ambient air can be prevented from entering the subway system by judicious selection of ventilation shaft locations. Particulate matter, including iron and graphite dust generated by normal train operations, is best controlled by regularly cleaning stations and tunnels. However, the only viable way to control gaseous contaminants in a subway system, such as ozone (produced by electrical equipment) and CO_2 (from human respiration), is through adequate ventilation with outdoor air.

Subway system air quality should be analyzed either by engineering calculations or by computer modeling and simulations. The analysis should consider both the tunnel airflow induced by the piston effect of moving trains and the outdoor airflow required to dilute gaseous contaminants to acceptable levels. The results should comply with the *Subway Environmental Design Handbook* (DOT 1976) recommendation for at least 4 ach, as well as the recommendation of ANSI/ASHRAE *Standard* 62.1 to have a minimum of 0.0071 m^3/s outdoor air per person. Maximum station occupancy should be used in the analysis.

Pressure Transients. Trains passing through aerodynamic discontinuities in a subway cause changes in tunnel static pressure, which can irritate passengers' ears and sinuses. Based on nuisance factor criteria, if the total change in the air pressure is greater than 697 Pa, the rate of static pressure change should be kept below 423 Pa/s. Pressure transients also add to the dynamic load on various equipment (e.g., fans, dampers) and appurtenances (e.g., acoustical panels). The formula and methodology of pressure transient calculations are complex; this information is presented in the SEDH (DOT 1976).

Air Velocity. During fires, emergency ventilation must be provided in the tunnels to control smoke flow and reduce air temperatures to permit both passenger evacuations and firefighting operations. The minimum air velocity in the affected tunnel should be sufficient to prevent smoke from backlayering (flowing in the upper cross section of the tunnel in the direction opposite the forced ventilation airflow). The method for ascertaining this critical air velocity is provided in the section on Design Approach, under Tunnels. The maximum tunnel air velocity experienced by evacuating passengers should not exceed 11 m/s.

Interior Heat Loads. Heat in a subway is generated mostly by the following sources:

- Train deceleration/braking: Between 40 and 50% of heat generated in a subway arises from train deceleration/braking. Many vehicles use nonregenerative braking systems, in which the kinetic energy of the train is dissipated to the tunnel as heat, through dynamic and/or frictional brakes, rolling resistance, and aerodynamic drag. Regenerative systems dissipate less braking heat.
- Train acceleration: Heat is also generated as a train accelerates. Many vehicles use cam-controlled variable-resistance elements to regulate voltage across dc traction motors during acceleration. Electrical power is dissipated by these resistors (and the third rail) as heat into the subway. The heat released during train acceleration also comes from traction motor losses, rolling resistance, and aerodynamic drag. Heat from acceleration generally amounts to 10 to 20% of the total heat released in a subway system.

In subway systems with closely spaced stations, more heat is generated because of the frequent acceleration and deceleration.

- Vehicle air conditioning: Most new transit vehicles are fully climate controlled. Air-conditioning equipment removes passenger and lighting heat from the cars and transfers it, along with condenser fan and compressor heat, into the subway. Vehicle air-conditioning system capacities generally range from 35 kW per vehicle for shorter rail cars (about 15 m long), up to about 70 kW for longer rail cars (about 21 m long). Heat from vehicle air conditioning and other accessories is generally 25 to 30% of total heat generated in a subway.

- Other sources: Tunnel heat also comes from people, lighting, induced outdoor air, miscellaneous equipment (e.g., fare collecting machines, escalators), and third-rail/catenary systems. These sources can generate 10 to 30% of the total heat released in a subway.

In a typical subway heat balance analysis, a control volume is defined around each station and heat sources are identified and quantified. The control volume usually includes the station and its various approach/departure tunnels. Typical values for heat emission/rejection data are given in Table 6.

Heat Sink. The amount of heat flow from tunnel air to subway walls varies seasonally, as well as during morning and evening rush-hour operations. Short periods of abnormally high or low outdoor temperature may cause a temporary departure from the normal heat sink effect in unconditioned areas of the subway, changing the average tunnel air temperature. However, any change from the normal condition is diminished by the thermal inertia of the subway structure. During abnormally hot periods, heat flow from the tunnel air to subway walls increases. Similarly, during abnormally cold periods, heat flow from the subway walls to tunnel air increases.

For subway systems where daily station air temperatures are held constant by dedicated heating and cooling systems, heat flux from station walls is negligible. Depending on the amount of station air flowing into adjoining tunnels, heat flux from tunnel sections may also be reduced. Other factors affecting the heat sink component are soil type (dense rock or light, dry soil), extent of migrating groundwater or the local water table, and surface configuration of tunnel walls (ribbed or flat).

Measures to Limit Heat Loads. Various measures have been proposed to limit interior heat loads in subway systems, including regenerative braking, thyristor motor controls, track profile optimization, underplatform exhaust systems, and cooling dumping.

Electrical regenerative braking converts kinetic energy into electrical energy for use by other trains. Flywheel energy storage, an alternative form of regenerative braking, stores part of the braking energy in high-speed flywheels for use during vehicle acceleration. These methods can reduce the heat generated in train braking by approximately 25%.

Cam-controlled propulsion applies a set of resistance elements to regulate traction motor current during acceleration. Electrical energy dissipated by these resistors appears as waste heat in a subway. **Thyristor motor controls** replace the acceleration resistors with solid-state controls, which reduce acceleration-related heat losses by about 10% on high-speed subways, and by about 25% on low-speed subways.

Track profile optimization refers to a tunnel design that is lower between the stations. Less power is used for acceleration, because some of the potential energy of a standing train is converted to kinetic energy as the train accelerates toward the tunnel low point. Conversely, some of the kinetic energy of a train at maximum speed is converted to potential energy during braking, as the train approaches the next station. Track profile optimization reduces the maximum vehicle heat loss from acceleration and braking by about 10%.

Table 6 Typical Heat Source Emission Values

Source of Heat	Heat Rejection, kW
Train A/C system (per vehicle)	42
Escalator (7.5 kW, 75% load factor)	5.6[a]
Fare collection machine	0.8[a]
Station lighting	0.032 per square metre[a]
People (walking, standing)	0.073 sensible[b]
	0.073 latent[b]

[a] See *Subway Environmental Design Handbook*, Part 3 (DOT 1976).
[b] See 2013 *ASHRAE Handbook—Fundamentals*, Chapter 9.

An **overtrack exhaust (OTE)** and/or **underplatform exhaust (UPE)** system, described in the section on Mechanical Ventilation, uses extract grilles at regular intervals to remove heat generated by vehicle equipment located either at car roof level or under the car (e.g., resistors, compressors, air-conditioning condensers) from the station environment. For forced-blown resistor grids and cases where the airflow pattern is well controlled over the source of the undercar heat, SEDH (DOT 1976) provides a table (based on field test results in a given station platform geometry) of various UPE airflow rates versus UPE system efficiency. Care should be taken when extending these data to other platform geometries. For preliminary calculations, it may be assumed that (1) the train heat release (from braking and air conditioning) in the station box is about two-thirds of the control-volume heat load, and (2) the UPE is about 50% effective (provided the geometry and airflow pattern conditions are fulfilled). Sanchez (2003) studied the impact of OTE/UPE for air-conditioned stations.

In tropical areas, where there are only small daily differences in the ambient air temperature, tunnel walls do not cool off during the night; consequently the heat sink effect is negligible. In such cases, **cooling dumping** (releasing cooler air from the vehicle or its air-conditioning system) can be considered to limit heat accumulation in subway tunnels. However, the effect of cooling dumping on vehicle air-conditioning systems must be considered.

Railroad Tunnels

Railroad tunnels for diesel locomotives require ventilation to remove residual diesel exhaust, so that each succeeding train is exposed to a relatively clean air environment. Ventilation is also required to prevent locomotives from overheating while in the tunnel. For short tunnels, ventilation generated by the piston effect of a train, followed by natural ventilation, is usually sufficient to purge the tunnel of diesel exhaust in a reasonable time period. Mechanical ventilation for locomotive cooling is usually not required in short tunnels, because the time that a train is in the tunnel is typically less than the time it would take for a locomotive to overheat. However, under certain conditions, such as for excessively slow trains or during hot weather, locomotive overheating can still become a problem. For long tunnels, mechanical ventilation is required to purge the tunnel of diesel exhaust, and may also be required for locomotive cooling, depending on the speed of the train and the number and arrangement of locomotives used.

The diesel locomotive is essentially a fuel-driven, electrically powered vehicle. The diesel engine drives a generator, which in turn supplies electrical power to the traction motors. The power of these engines ranges from about 750 to 4500 kW. Because the overall efficiency of the locomotive is generally under 30%, most of the energy generated by the combustion process must be dissipated as heat to the surrounding environment. Most of this heat is released above the locomotive through the engine exhaust stack and the radiator discharge (Figure 12).

In a tunnel, this heat is confined to the region surrounding the train. Most commercial trains are powered by more than one locomotive, so the last unit is subjected to heat and exhaust smoke released by preceding units. If sufficient ventilation is not provided, the air temperature entering the radiator of the last locomotive will exceed its allowable limit. Depending on the engine protection system, this locomotive will then either shut down or drop to a lower throttle position. In either event, the train will slow down. But, as discussed in the next section, a train relies on its speed to generate sufficient ventilation for cooling. As a result of the train slowing down, a domino effect takes place, which may cause the train to stall in the tunnel.

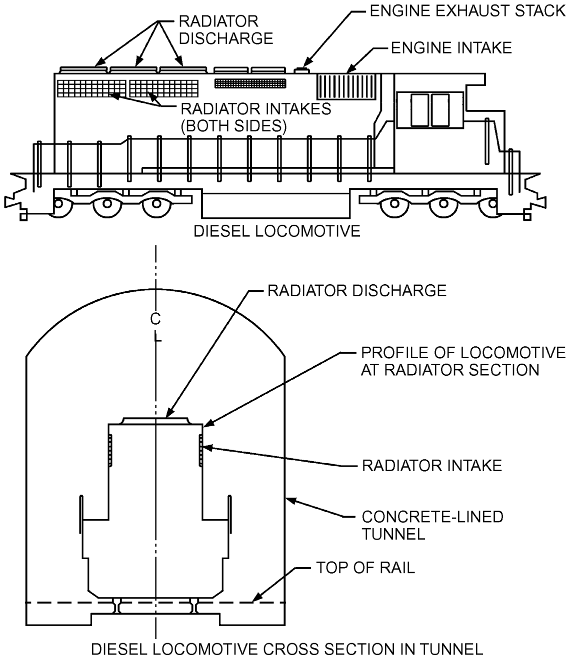


Fig. 12 Typical Diesel Locomotive Arrangement

Design Concepts. Most long railroad tunnels (over 8 km) in the western hemisphere that serve diesel operation use a ventilation concept using both a tunnel door and a system of fans and dampers, all located at one end of the tunnel. When a train moves through the tunnel, ventilation air for locomotive cooling is generated by the piston effect of the train moving toward (or away from) the closed portal door. This effect often creates a sufficient flow of air past the train for self-cooling.

Under certain conditions, when the piston effect cannot provide required airflow, fans supplement the flow and cool the tunnel. When the train exits at the portal, the tunnel is purged of residual smoke and diesel contaminants by running the fans (with the door closed) to move fresh air from one end of the tunnel to the other. Because the airflow and pressure required for cooling and purge modes may be substantially different, multiple fan systems or variable-volume fans may be required for the two operations. Also, dampers are provided to relieve the pressure across the door, which facilitates its operation while the train is in the tunnel.

Application of this basic ventilation concept varies depending on the length and grade of the tunnel, type and speed of the train, environmental and structural site constraints, and train traffic flow. One design, for a 14.5 km long tunnel (Levy and Danziger 1985), extended the basic concept by including a mid-tunnel door and a partitioned shaft, which was connected to the tunnel on both sides of the mid-tunnel door. The combination of mid-tunnel door and partitioned shaft divided the tunnel into two segments, each with its own ventilation system. Thus, the ventilation requirement of each segment was satisfied independently. The need for such a system was dictated by the length of the tunnel, relatively low speed of the trains, and traffic pattern.

Locomotive Cooling Requirements. A breakdown of the heat emitted by a locomotive to the surrounding air can be determined by performing an energy balance. Starting with the fuel consumption rate (as a function of the throttle position), the heat release rates (as provided by the engine manufacturer) at the engine exhaust stack and radiator discharge, and the gross power delivered by the engine shaft (as determined from manufacturer's data), the amount of miscellaneous heat radiated by a locomotive can be determined as follows:

$$q_M = FH - q_S - q_R - P_G \tag{9}$$

where

q_M = miscellaneous heat radiated from locomotive engine, W
F = locomotive fuel consumption, kg/s
H = heating value of fuel, J/kg
q_S = heat rejected at engine exhaust stack, W
q_R = heat rejected at radiator discharge, W
P_G = gross power at engine shaft, W

Because locomotive auxiliaries are driven off the engine shaft, with the remaining power used for traction power through the main engine generator, heat released by the main engine generator can be determined as follows:

$$q_G = (P_G - L_A)(1 - \varepsilon_G) \tag{10}$$

where

q_G = main generator heat loss, W
L_A = power driving locomotive auxiliaries, W
ε_G = main generator efficiency

Heat loss from the traction motors and gear trains can be determined as follows:

$$q_{TM} = P_G - L_A - q_G - P_{TE} \tag{11}$$

where

q_{TM} = heat loss from traction motors and gear trains, W
P_{TE} = locomotive tractive effort power, W

The total locomotive heat release rate q_T can then be determined:

$$q_T = q_S + q_R + q_m + L_A + q_G + q_{TM} \tag{12}$$

For a train with N locomotives, the average air temperature approaching the last locomotive is determined from

$$t_{AN} = t_{AT} + \frac{q_T(N-1)}{\rho c_p Q_R} \tag{13}$$

where

t_{AN} = average tunnel air temperature approaching Nth locomotive, °C
t_{AT} = average tunnel air temperature approaching locomotive consist, °C
ρ = density of tunnel air approaching locomotive consist, kg/m^3
c_p = specific heat of air, J/(kg·°C)
Q_R = tunnel airflow rate relative to train, m^3/s

The inlet air temperature to the locomotive radiators is used to judge the adequacy of the ventilation system. For most locomotives running at maximum throttle position, the maximum inlet air temperature recommended by manufacturers is about 46°C. Field tests in operating tunnels (Aisiks and Danziger 1969; Levy and Elpidorou 1991) showed, however, that some units can operate continuously with radiator inlet air temperatures as high as 57°C. The allowable inlet air temperature for each locomotive type should be obtained from the manufacturer when contemplating a design.

To determine the airflow rate required to prevent a locomotive from overheating, the relationship between the average tunnel air temperature approaching the last unit and the radiator inlet air temperature must be known or conservatively estimated. This relationship depends on variables such as the number of locomotives in the consist, air velocity relative to the train, tunnel cross-sectional area/configuration, type of tunnel lining, and locomotive orientation (i.e., facing forward or backward). For trains traveling under 32 km/h, Levy and Elpidorou (1991) showed that a reasonable estimate is to assume the radiator inlet air temperature to be about 6 K higher than the average air temperature approaching the unit. For trains moving at 50 km/h or more, a reasonable estimate is to assume that the radiator inlet air temperature equals the average air temperature approaching the unit. When the last unit of the train consist faces forward, thereby putting the exhaust stack ahead of its own radiators, the stack heat release rate must be included when evaluating the radiator inlet air temperature.

Tunnel Aerodynamics. When designing a ventilation system for a railroad tunnel, airflow and pressure distribution throughout the tunnel (as a function of train type, train speed, and ventilation system operating mode) must be determined. This information is required to determine (1) whether sufficient ventilation is provided for locomotive cooling, (2) the pressure that the fans are required to deliver, and (3) the pressure that the structural and ventilation elements of the tunnel must be designed to withstand.

The following equation, from DOT (1997a), relates the piston effect of the train, steady-state airflow from fans to the tunnel, and pressure across the tunnel door. This expression assumes that air leakage across the tunnel door is negligible. Figure 13 shows the dimensional variables on a schematic of a typical tunnel.

$$\begin{aligned}\frac{\Delta p}{\rho} &= \frac{(p_A - p_B)}{\rho} - \frac{Hg}{g_C} \\ &+ \left(\frac{(A_V^2 + A_V A_T C_{DVB})}{(A_T - A_V)^2} + \frac{A_V C_{DVF}}{A_T}\right)\frac{(A_T V + Q_S)^2}{2A_T^2 g_C} \\ &+ \frac{f_T L_V P_T (A_V V + Q_S)^2}{8(A_T - A_V)^3 g_C} + \frac{\lambda_V L_V P_V (A_T V + Q_S)^2}{8(A_T - A_V)^3 g_C} \\ &+ \frac{f_T (L_T - L_V) P_T Q_S^2}{8A_T^3 g_C} + \frac{K Q_S^2}{2A_T^2 g_C}\end{aligned} \qquad (14)$$

where

Δp = static pressure across tunnel door, Pa
ρ = density of air, kg/m^3
p_A = barometric pressure at portal A, Pa
p_B = barometric pressure at portal B, Pa
H = difference in elevation between portals, m
g = acceleration of gravity = 9.81 m/s^2
g_C = gravitational constant = 1.0 (m·kg)/N·s^2
A_V = train cross-sectional area, m^2
A_T = tunnel cross-sectional area, m^2
C_{DVB} = drag coefficient at back end of train
C_{DVF} = drag coefficient at front end of train
V = velocity of train, m/s
Q_S = airflow delivered by fan, m^3/s
f_T = tunnel wall friction factor
L_T = tunnel length, m
L_V = train length, m
P_T = tunnel perimeter, m
P_V = train perimeter, m
λ_V = train skin friction factor
K = miscellaneous tunnel loss coefficient

The pressure across the tunnel door generated only by train piston action is evaluated by setting Q_S equal to zero. The airflow rate, relative to the train, required to evaluate locomotive cooling requirements is

$$Q_{rel} = A_T V + Q_S \qquad (15)$$

where Q_{rel} is the airflow rate relative to the train, m^3/s.

Typical values for C_{DVB} and C_{DVF} are about 0.5 and 0.8, respectively. Because trains passing through a railroad tunnel are often more than 1.6 km long, the parameter that most affects the generated air pressure is the train skin friction coefficient. For dedicated coal or grain trains, which essentially use uniform cars throughout, a value of 0.09 for the skin friction coefficient results in air pressure predictions that conform closely to those observed in various railroad tunnels. For trains with nonuniform car distribution, the skin friction coefficient may be as high as 1.5 times that for a uniform car distribution.

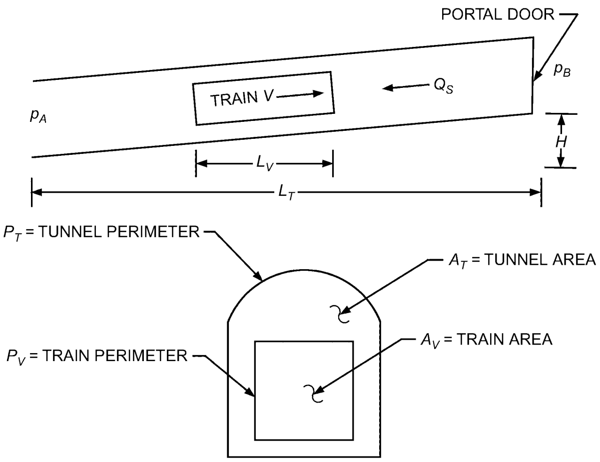


Fig. 13 Railroad Tunnel Aerodynamic Related Variables

The wall surface friction factor corresponds to the coefficient used in the Darcy-Weisbach equation for friction losses in pipe flow. Typical effective values for tunnels constructed with a formed concrete lining and having a ballasted track range from 0.015 to 0.017.

Tunnel Purge. The leading end of a locomotive must be exposed to an environment that is relatively free of smoke and diesel contaminants emitted by preceding trains. Railroad tunnels are usually purged by displacing contaminated tunnel air with fresh air by mechanical means after a train has left the tunnel. With the tunnel door closed, air is either supplied to or exhausted from the tunnel, moving fresh air from one end of the tunnel to the other. Observations at the downstream end of tunnels have found that an effective purge time is usually based on displacing 1.25 times the tunnel volume with outdoor air.

The time required for purging is primarily determined by operations schedule needs. A long purging time limits traffic; a short purging time may necessitate very high ventilation airflow rates and result in high electrical energy demand and consumption. Consequently, multiple factors must be considered, including the overall ventilation concept, when establishing the purge rate.

2. PARKING GARAGES

Automobile parking garages can be either fully enclosed or partially open. Fully enclosed parking areas are often underground and require mechanical ventilation. Partially open parking garages are generally above-grade structural decks having open sides (except for barricades), with a complete deck above. Natural ventilation, mechanical ventilation, or a combination can be used for partially open garages.

Operating automobiles in parking garages presents two concerns. The more serious is emission of CO, with its known risks. The other concern is oil and gasoline fumes, which may cause nausea and headaches and also represent potential fire hazards. Additional concerns about NO$_x$ and smoke haze from diesel engines may also require consideration. However, the ventilation rate required to dilute CO to acceptable levels is usually satisfactory to control the level of other contaminants as well, provided the percentage of diesel vehicles does not exceed 20%.

For many years, the various model codes, ANSI/ASHRAE *Standard* 62.1, and its predecessor standards recommended a flat exhaust rate of either 0.0075 $m^3/(s \cdot m^2)$ or 6 ach for enclosed parking garages. But because vehicle emissions have been reduced over the years, ASHRAE sponsored a study to determine ventilation rates required to control contaminant levels in enclosed parking facilities (Krarti and Ayari 1998). The study found that, in some cases, much less ventilation than 0.0075 $m^3/(s \cdot m^2)$ was satisfactory. The study's methodology for determining whether a reduced ventilation rate would be effective is included below. However, ANSI/ASHRAE *Standard* 62.1 and the International Code Council's *International Mechanical Code*® (ICC 2009a) allow 0.00375 $m^3/(s \cdot m^2)$ ventilation, whereas NFPA *Standard* 88A recommends a minimum of 0.005 $m^3/(s \cdot m^2)$, so the engineer must understand the specific codes and standards that apply. The engineer may be required to request a variation, or waiver, from authorities having jurisdiction before implementing a lesser ventilation system design.

If larger fans are installed to meet code requirements, they will not necessarily increase overall power consumption; with proper CO level monitoring and ventilation system control, fans will run for shorter time periods to maintain acceptable CO levels. With increased attention on reducing energy consumption, CO-based ventilation system control can provide substantial cost savings in the operation of parking garages.

Ventilation Requirements and Design

ASHRAE research project RP-945 (Krarti and Ayari 1998) found that the design ventilation rate required for an enclosed parking facility depends chiefly on four factors:

- Acceptable level of contaminants in the parking facility
- Number of cars in operation during peak conditions
- Length of travel and the operating time for cars in the garage
- Emission rate of a typical car under various conditions

Contaminant Level Criteria. ACGIH (1998) recommends a threshold CO limit of 29 mg/m^3 (25 ppm) for an 8 h exposure, and the U.S. EPA (2000) determined that exposure, at or near sea level, to a CO concentration of 40 mg/m^3 (35 ppm) for up to 1 h is acceptable. For parking garages more than 1000 m above sea level, more stringent limits are required.

In Europe, an average concentration of 40 mg/m^3 (35 ppm) and a maximum level of 230 mg/m^3 (200 ppm) are usually maintained in parking garages.

Various agencies and countries differ on the acceptable level of CO in parking garages, but a reasonable solution is a ventilation rate designed to maintain a CO level of 40 mg/m^3 (35 ppm) for 1 h exposure, with a maximum of 29 mg/m^3 (25 ppm) for an 8 h exposure. Because the time associated with driving in and parking, or driving out of a garage, is on the order of minutes, 40 mg/m^3 (35 ppm) is probably an acceptable level of exposure. However, Figure 14 provides nomographs for 15 and 25 ppm maximum exposures as well, to allow the designer to conform to more stringent regulations.

Number of Cars in Operation. The number of cars operating at any one time depends on the type of facility served by the parking garage. For distributed, continuous use, such as an apartment building or shopping area, the variation is generally 3 to 5% of the total vehicle capacity. The operating capacity could reach 15 to 20% in other facilities, such as sports stadiums or short-haul airports.

Length of Time of Operation. The length of time that a car remains in operation in a parking garage is a function of the size and layout of the garage, and the number of cars attempting to enter or exit at a given time. The operating time could vary from as much as 60 to 600 s, but on average usually ranges from 60 to 180 s. Table 7 lists approximate data for average vehicle entrance and exit times; these data should be adjusted to suit the specific physical configuration of the facility.

Car Emission Rate. Operating a car in a parking garage differs considerably from normal vehicle operation, including that in a road tunnel. Most car movements in and around a parking garage occur in low gear. A car entering a garage travels slowly, but the engine is usually hot. As a car exits from a garage, the engine is usually cold and operating in low gear, with a rich fuel mixture. Emissions for a cold start are considerably higher, so the distinction between hot and cold emission plays a critical role in determining the ventilation rate. Motor vehicle emission factors for hot- and cold-start operation are presented in Table 8. An accurate analysis requires correlation of CO readings with the survey data on car movements (Hama et al. 1974); the data should be adjusted to suit the specific physical configuration of the facility and the design year.

Design Method. To determine the design airflow rate to ventilate an enclosed parking garage, the following procedure can be used:

Step 1. Collect the following data:

- Number of cars N in operation during peak hour use
- Average CO emission rate E for a typical car, g/h
- Average length of operation and travel time θ for a typical car, s
- Acceptable CO concentration CO_{max} in the garage, ppm
- Total floor area of parking facility A_f, m^2

Step 2. Evaluate CO generation rate:

(1) Determine the peak CO generation rate per unit floor area G, in $g/(h \cdot m^2)$, for the parking garage:

$$G = NE/A_f \tag{16}$$

(2) Normalize the peak CO generation rate using the reference value $G_0 = 26.7\ g/(h \cdot m^2)$ and Equation (17). This reference value is based on an actual enclosed parking facility (Krarti and Ayari 1998):

$$f = 100G/G_0 \tag{17}$$

Step 3. Determine the minimum required ventilation rate Q per unit floor area using Figure 14, or the correlation presented by Equation (18), depending on CO_{max}:

$$Q = C f \theta \tag{18}$$

where

$C = 1.204 \times 10^{-6}\ (m^3/s)/(m^2/s)$ for $CO_{max} = 15$ ppm
$= 0.692 \times 10^{-6}\ (m^3/s)/(m^2/s)$ for $CO_{max} = 25$ ppm
$= 0.481 \times 10^{-6}\ (m^3/s)/(m^2/s)$ for $CO_{max} = 35$ ppm

Example 1. Consider a two-level enclosed parking garage with a total capacity of 450 cars, a total floor area of 8360 m^2, and an average height of 2.75 m. The total length of time for a typical car operation is

Table 7 Average Entrance and Exit Times for Vehicles

Level	Average Entrance Time, s	Average Exit Time, s
1	35	45
3*	40	50
5	70	100

Source: Stankunas et al. (1980). *Average pass-through time = 30 s.

Table 8 Predicted CO Emissions in Parking Garages

	Hot Emission (Stabilized), g/min		Cold Emission, g/min	
Season	1991	1996	1991	1996
Summer, 32°C	2.54	1.89	4.27	3.66
Winter, 0°C	3.61	3.38	20.74	18.96

Results from EPA MOBILE3, version NYC-2.2 (1984); sea level location.
Note: Assumed vehicle speed is 8 km/h.

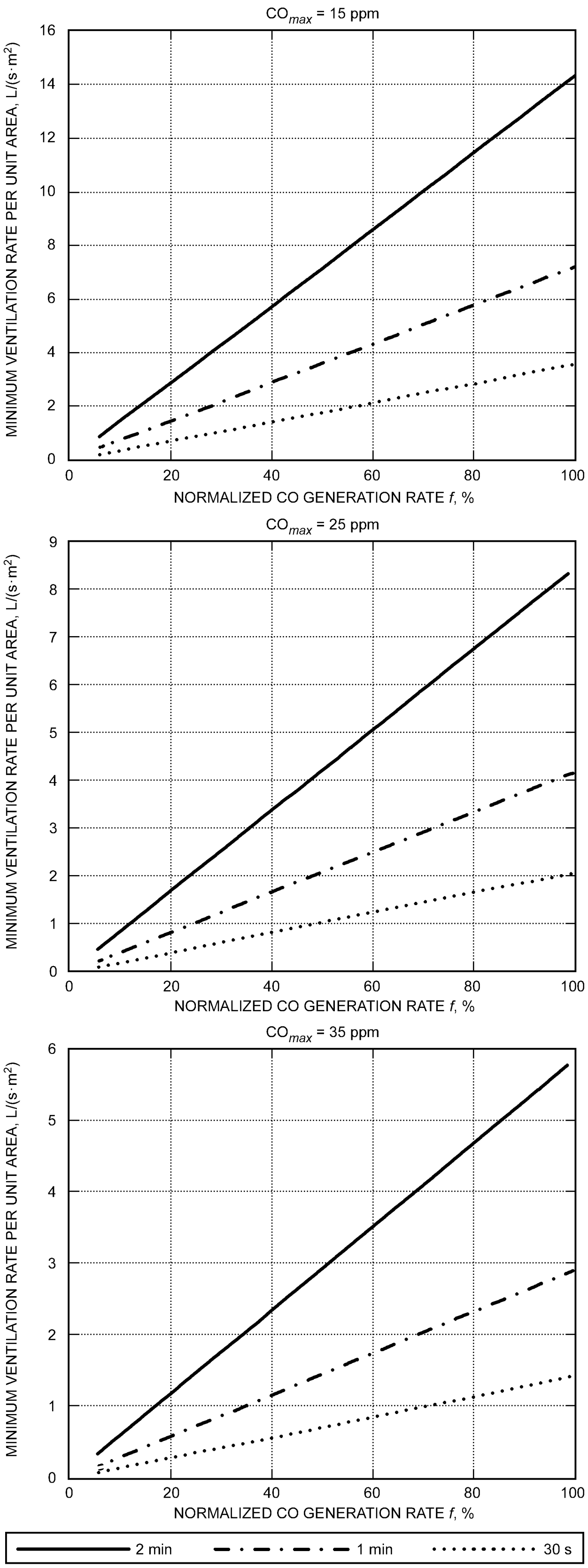


Fig. 14 Ventilation Requirement for Enclosed Parking Garage

2 min (120 s). Determine the required ventilation rate for the enclosed parking garage in $m^3/(s \cdot m^2)$ and in air changes per hour so that the CO level never exceeds 25 ppm. Assume that the number of cars in operation during peak use is 40% of the total vehicle capacity.

Solution:

Step 1. Garage data:

N = $450 \times 0.4 = 180$ cars
E = 11.67 g/min = 700 g/h, the average of all values of emission rate for a winter day, from Table 8
CO_{max} = 25 ppm
θ = 120 s

Step 2. Calculate the normalized CO generation rate:

$G = (180 \times 700 \text{ g/h})/8360 \text{ m}^2 = 15.1 \text{ g/(h}\cdot\text{m}^2)$
$f = 100 \times (15.1 \text{ g/h}\cdot\text{m}^2)/26.7 \text{ g/(h}\cdot\text{m}^2) = 56.6$

Step 3. Determine the ventilation requirement, using Figure 14 or the correlation of Equation (18) for CO_{max} = 25 ppm.

$$Q = 0.692 \times 10^{-6} \text{ (m}^3\text{/s)/(m}^2\cdot\text{s)} \times 56.6 \times 120 \text{ s} = 0.0047 \text{ m}^3\text{/(s}\cdot\text{m}^2)$$

Or, for air changes per hour,

$$(0.0047 \text{ (m}^3\text{/s)/m}^2 \times 3600 \text{ s/h})/2.74 \text{ m} = 6.2$$

Notes:

1. If the average vehicle CO emission rate is reduced to E = 6.60 g/min, because of, for instance, better emission standards or better maintained cars, the required minimum ventilation rate decreases to 0.0027 $m^3/(s \cdot m^2)$ or 3.5 ach.

2. Once calculations are made and a decision reached to use CO demand ventilation control, increasing airflow through a safety margin does not increase operating costs; larger fans work for shorter periods to sweep the garage and maintain satisfactory conditions.

CO Demand Ventilation Control. Whether mechanical, natural, or both, a parking garage ventilation system should meet applicable codes and maintain acceptable contaminant levels. If permitted by local codes, the ventilation airflow rate should be varied according to CO levels to conserve energy. For example, the ventilation system could consist of multiple fans, with single- or two-speed motors, or variable-pitch blades. In multilevel parking garages or single-level structures of extensive area, independent fan systems with individual controls are preferred. The *International Mechanical Code*® (ICC 2009a) allows ventilation system operation to be reduced from 0.00375 to 0.00025 $m^3/(s \cdot m^2)$ with the use of a CO monitoring system that restores full ventilation when CO levels of 29 mg/m^3 (25 ppm) are detected.

Figure 15 shows the maximum CO level in a tested parking garage (Krarti and Ayari1998) for three car movement profiles (Figure 16) and the following ventilation control strategies:

- Constant-volume (CV), where the ventilation system is kept on during the entire occupancy period
- On/off control, with fans stopped and started based on input from CO sensors
- Variable-air-volume (VAV) control, using either two-speed fans or axial fans with variable-pitch blades, based on input from CO sensors

Figure 15 also shows typical fan energy savings achieved by on/off and VAV systems relative to constant-volume systems. Significant fan energy savings can be obtained using a CO-based demand ventilation control strategy to operate the ventilation system, maintaining CO levels below 29 mg/m^3 (25 ppm). Wear and tear and maintenance on mechanical and electrical equipment are reduced with a CO-based demand strategy.

Figure 16 is based on maintaining a 29 mg/m^3 (25 ppm) CO level. With most systems, actual energy usage is further reduced if 40 mg/m^3 (35 ppm) is maintained.

In cold climates, the additional cost of heating makeup air is also reduced with a CO-based demand strategy. Energy stored in the mass of the structure usually helps maintain the parking garage air temperature at an acceptable level. If only outdoor air openings are used to draw in ventilation air, or if infiltration is allowed, the stored energy is lost to the incoming cold air.

Ventilation System Configuration. Parking garage ventilation systems can be classified as supply-only, exhaust-only, or combined. Regardless of which system design is chosen, the following elements should be considered in planning the system configuration:

- Accounting for the contaminant level of outdoor air drawn in for ventilation
- Avoiding short-circuiting supply air
- Avoiding a long flow field that allows contaminants to exceed acceptable levels at the end of the flow field
- Providing short flow fields in areas of high contaminant emission, thereby limiting the extent of mixing
- Providing efficient, adequate airflow throughout the structure
- Accounting for stratification of engine exhaust gases when stationary cars are running in enclosed facilities

Other Considerations. Access tunnels or long, fully enclosed ramps should be designed in the same way as road tunnels. When natural ventilation is used, wall openings or free area should be as large as possible. Part of the free area should be at floor level.

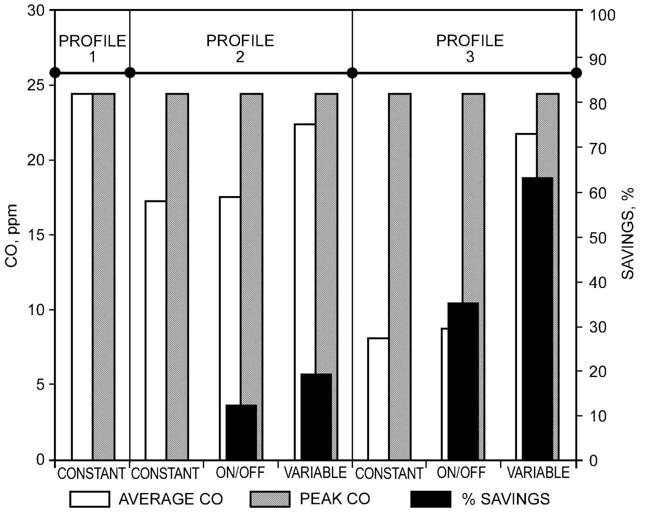


Fig. 15 Typical Energy Savings and Maximum CO Level Obtained for Demand CO-Ventilation Controls

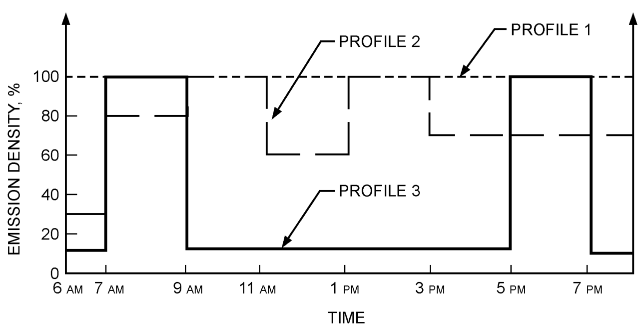


Fig. 16 Three Car Movement Profiles

For parking levels with large interior floor areas, a central emergency smoke exhaust system should be considered for removing smoke (in conjunction with other fire emergency systems) or vehicle fumes under normal conditions.

Noise. In general, parking garage ventilation systems move large quantities of air through large openings without extensive ductwork. These conditions, and the highly reverberant nature of the space, contribute to high noise levels, so sound attenuation should be considered in the ventilation system design. This is a pedestrian safety concern, as well, because high fan noise levels in a parking garage may mask the sound of an approaching vehicle.

Ambient Standards and Contaminant Control. Air exhausted from a parking garage should meet state and local air pollution control requirements.

3. AUTOMOTIVE REPAIR FACILITIES

Automotive repair activities are defined as any repair, modification, service, or restoration activity to a motor vehicle. This includes, but is not limited to, brake work, engine work, machining operations, and general degreasing of engines, motor vehicles, parts, or tools.

ANSI/ASHRAE *Standard* 62.1 recommends a ventilation rate of 0.0075 $m^3/(s \cdot m^2)$ for automotive service stations; the *International Mechanical Code*® (ICC 2009a) allows 0.00375 $m^3/(s \cdot m^2)$. The designer must determine which code is applicable. The high ventilation rate indicates that contaminants are not related to the occupants, but are produced by the variety of tasks and materials used in the facility. Outdoor ventilation is introduced into the space and an approximately equal quantity is exhausted through a dedicated exhaust system.

As repairs or maintenance are performed on vehicles, it may be necessary to operate the vehicle inside the facility to test and validate the work. Additional mechanical ventilation is required to exhaust combustion by-products directly outdoors. An independent source capture system that connects directly to the exhaust pipe of the vehicle must be installed in the facility. These systems are available in either an above- or belowground configuration. Flow rates for individual service bays vary from 0.024 to 0.190 m^3/s for automobiles. A large diesel truck will require considerably more airflow per service bay than an automobile.

The above-grade system consists of an exhaust fan, associated ductwork, and flexible hoses that attach to the tailpipe of the vehicle in operation. Generally, the system is installed at a high elevation to maintain maximum clearances above floor level. The hose connections are stored in reels positioned near each service bay. The service technician pulls the hose down and attaches it to the tailpipe by a proprietary connection.

The below-grade system is similar in design to an overhead exhaust system. Care must be taken to select an appropriate corrosion-resistant material to be installed underground, because the condensing products of combustion are corrosive to traditional duct materials. The flexible tailpipe exhaust connectors are stored inside the underground duct. After sliding the flex back inside the duct, a hinged cover plate covers the opening flush to the floor.

Although there is a diversity factor in the system capacity calculations, both systems must be designed to operate at 100% capacity. A constant-volume fan is used, with all air being exhausted from the space. With a single outlet in use, some means of relief is provided to maintain constant flow through the fan. This equipment can be set up to run continuously or intermittently. Intermittent use requires the general exhaust system to vary between the maximum supply air delivered to the space when the capture system is in use and a lower exhaust flow rate reduced by the amount of air exhausted through the capture system.

4. BUS GARAGES

Bus garages generally include a maintenance and repair area, service lane (where buses are fueled and cleaned), storage area (where buses are parked), and support areas such as offices, stock room, lunch room, and locker rooms. The location and layout of these spaces can depend on factors such as local climate, size of the bus fleet, and type of fuel used by the buses. Bus servicing and storage areas may be located outdoors in a temperate region, but are often inside in colder climates. However, large bus fleets cannot always be stored indoors; for smaller fleets, maintenance areas may double as storage space. Local building and/or fire codes may also prohibit dispensing certain types of fuel indoors.

In general, bus maintenance or service areas should be ventilated using 100% outdoor air with no recirculation. Therefore, using heat recovery devices should be considered in colder climates.

Tailpipe emissions should be exhausted directly from buses at fixed inspection and repair stations in maintenance areas. Offices and similar support areas should be kept under positive pressure to prevent infiltration of bus emissions.

Maintenance and Repair Areas

ANSI/ASHRAE *Standard* 62.1 recommends a minimum ventilation of 0.0075 $m^3/(s \cdot m^2)$ and the *International Mechanical Code®* (ICC 2009a) recommends 0.00375 $m^3/(s \cdot m^2)$ of floor area in vehicle repair garages, with no recirculation. The designer should determine which code is applicable. However, because the interior ceiling height may vary greatly from garage to garage, the designer should consider making a volumetric analysis of contaminant generation and air exchange rates. The section on Bus Terminals contains information on diesel engine emissions and ventilation airflow rates needed to control contaminant concentrations in areas where buses are operated.

Maintenance and repair areas often include below-grade inspection and repair pits for working underneath buses. Because vapors produced by conventional bus fuels are heavier than air, they tend to settle in these pit areas, so a separate exhaust system should be provided to prevent their accumulation. NFPA *Standard* 30A recommends a minimum of 0.005 $m^3/(s \cdot m^2)$ in pit areas and the installation of exhaust registers near the floor of the pit.

Fixed repair stations, such as inspection/repair pits or hydraulic lift areas, should include a direct exhaust system for tailpipe emissions. Such direct exhaust systems have a flexible hose and coupling attached to the bus tailpipe; emissions are discharged to the outdoors by an exhaust fan. The system may be of the overhead reel, overhead tube, or underfloor duct type, depending on the tailpipe location. For heavy diesel engines, a minimum exhaust rate of 0.28 m^3/s per station is recommended to capture emissions without creating excessive backpressure in the vehicle. Fans, ductwork, and hoses should be able to receive vehicle exhaust at temperatures exceeding 260°C without degradation.

Bus garages often include areas for battery charging, which can produce potentially explosive concentrations of corrosive, toxic gases. There are no published code requirements for ventilating battery-charging areas, but DuCharme (1991) suggested using a combination of floor and ceiling exhaust registers to remove gaseous by-products. The recommended exhaust rates are 0.0114 $m^3/(s \cdot m^2)$ of room area at floor level to remove acid vapors and 0.0038 $m^3/(s \cdot m^2)$ of room area at ceiling level to remove hydrogen gases. The associated supply air volume should be 10 to 20% less than exhaust air volume, but designed to provide a minimum terminal velocity of 0.5 m/s at floor level. If the battery-charging space is located in the general maintenance area rather than in a dedicated space, an exhaust hood should be provided to capture gaseous by-products. Chapter 32 contains specific information on exhaust hood design. Makeup air should be provided to replace that removed by the exhaust hood.

Garages may also contain spray booths, or rooms for painting buses. Most model codes reference NFPA *Standard* 33 for spray booth requirements; this standard should be reviewed when designing heating and ventilating systems for such areas.

Servicing Areas

For indoor service lanes, ANSI/ASHRAE *Standard* 62.1 recommends a minimum ventilation of 0.0075 $m^3/(s \cdot m^2)$ and the *International Mechanical Code®* (ICC 2009a) recommends 0.00375 $m^3/(s \cdot m^2)$ of floor area in vehicle repair garages, with no recirculation. The designer should determine which code is applicable. However, because the interior ceiling height may vary greatly from garage to garage, the designer should consider making a volumetric analysis of contaminant generation and air exchange rates. The section on Bus Terminals contains information on diesel engine emissions and ventilation airflow rates needed to control contaminant concentrations in areas where buses are operated.

Because of the increased potential for concentrations of flammable or combustible vapor, HVAC systems for bus service lanes should not be interconnected with systems serving other parts of the bus garage. Service-lane HVAC systems should be interlocked with fuel-dispensing equipment, to prevent operation of the latter if the former is shut off or fails. Exhaust inlets should be located both at ceiling level and 75 to 300 mm above the finished floor, with supply and exhaust diffusers/registers arranged to provide air movement across all planes of the dispensing area. A typical equipment arrangement is shown in Figure 17.

Another feature in some service lanes is the cyclone cleaning system: these devices have a dynamic connection to the front door(s) of the bus, through which a large-volume fan vacuums dirt and debris from inside the bus. A large cyclone assembly then removes dirt and debris from the airstream and deposits it into a large hopper for disposal. Because of the large volume of air involved, the designer should consider the discharge and makeup air systems required to complete the cycle. Recirculation and energy recovery should be considered, especially during winter. To aid in contaminant and heat removal during summer, some systems discharge the cyclone air to the outdoors and provide untempered makeup air through relief hoods above the service lane.

Storage Areas

Where buses are stored inside, the minimum ventilation standard is based upon the applicable code: 0.00375 $m^3/(s \cdot m^2)$ for the

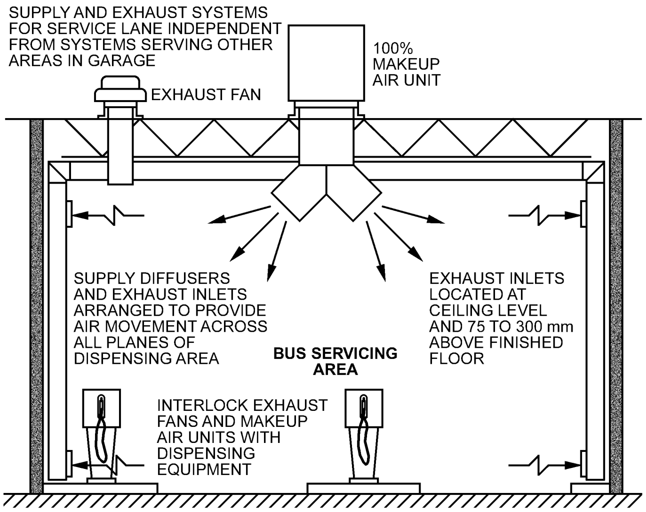


Fig. 17 Typical Equipment Arrangement for Bus Garage

International Mechanical Code®, or 0.0075 $m^3/(s \cdot m^2)$ for ANSI/ASHRAE *Standard* 62.1, subject to volumetric considerations. The designer should also consider the increased contaminant levels present during peak traffic periods.

One example is morning pullout, when the majority of the fleet is dispatched for rush-hour commute. It is common practice to start and idle a large number of buses during this period to warm up the engines and check for defects. As a result, the emissions concentration in the storage area rises, and additional ventilation may be required to maintain contaminant levels in acceptable limits. Using supplemental purge fans is a common solution to this problem. These purge fans can either be (1) interlocked with a timing device to operate during peak traffic periods, (2) started manually on an as-needed basis, or (3) connected to an air quality monitoring system that activates them when contaminant levels exceed some preset limit.

Design Considerations and Equipment Selection

Most model codes require that open-flame heating equipment, such as unit heaters, be located at least 2.4 m above the finished floor or, where located in active trafficways, 0.6 m above the tallest vehicle. Fuel-burning equipment outside the garage area, such as boilers in a mechanical room, should be installed with the combustion chamber at least 460 mm above the floor. Combustion air should be drawn from outside the building. Exhaust fans should be nonsparking, with their motors located outside the airstream.

Infrared heating systems and air curtains are often considered for bus repair garages because of the size of the facility and amount of infiltration through the large doors needed to move buses in and out of the garage. However, infrared heating must be used cautiously in areas where buses are parked or stored for extended periods, because the buses may absorb most of the heat, which is then lost when the buses leave the garage. This is especially true during morning pullout. Infrared heating can be applied with more success in the service lane or at fixed repair positions. Air curtains should be considered for high-traffic doorways to limit both heat loss and infiltration of cold air.

Where air quality monitoring systems control ventilation equipment, maintainability is a key factor in determining success of the application. The high concentration of particulate matter in bus emissions can adversely affect monitoring equipment, which often has filtering media at sampling ports to protect sensors and instrumentation. The location of sampling ports, effects of emissions fouling, and calibration requirements should be considered when selecting monitoring equipment to control ventilation systems and air quality of a bus garage. NO_2 and CO exposure limits published by OSHA and the EPA should be consulted to determine contaminant levels at which exhaust fans should be activated.

Effects of Alternative Fuel Use

Because of legislation limiting contaminant concentrations in diesel bus engine emissions, the transportation industry has begun using buses that operate on alternative fuels, including methanol, ethanol, hydrogen (and fuel cells), compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied petroleum gas (LPG). Flammability, emission, and vapor dispersion characteristics of these fuels differ from those of conventional fuels, for which current code requirements and design standards were developed. Thus, established ventilation requirements may not be valid for bus garage facilities used by alternative-fuel vehicles. The designer should consult current literature on HVAC system design for these facilities rather than relying on conventional practices. One source is the Alternative Fuels Data Center at the U.S. Department of Energy in Washington, D.C; their Web site (http://www.afdc.energy.gov) includes design recommendations for various alternative fuels. The DOT (1996a, 1996b, 1996c, 1997b, 1998) Volpe Transportation Center has also issued several guidelines for alternative-fuel bus facilities, which can be consulted for additional suggestions.

CNG Vehicle Facilities. For CNG bus facilities, NFPA *Standard* 52 recommends a separate mechanical ventilation system providing at least 0.017 m^3/s per 12 m^3, or 5 ach, for indoor fueling and gas processing/storage areas. The ventilation system should operate continuously or be activated by a continuously monitoring natural gas detector when a gas concentration of not more than 20% of the lower flammability limit (LFL) is present. The fueling or fuel-compression equipment should be interlocked to shut down if the mechanical ventilation system fails. Supply inlets should be located near floor level; exhaust outlets should be located high in the roof or exterior wall structure. The *International Mechanical Code*® (ICC 2009a) has identical requirements, except that it requires activation of the ventilation system at 25% of the LFL, and the requirements apply to maintenance and repair areas as well as indoor fueling facilities.

DOT (1996a) guidelines for CNG facilities address bus storage and maintenance areas, as well as bus fueling areas. DOT recommendations include (1) minimizing potential for dead-air zones and gas pockets (which may require coordination with architectural and structural designers); (2) using a normal ventilation rate of 6 ach, with provisions to increase that rate by an additional 6 ach in the event of a gas release; (3) using nonsparking exhaust fans rated for use in Class 1, Division 2 areas (as defined by NFPA *Standard* 70); and (4) increasing the minimum ventilation rate in smaller facilities to maintain dilution levels similar to those in larger facilities. Open-flame heating equipment should not be used, and the surface temperature of heating units should not exceed 425°C. In the event of a gas release, deenergizing supply fans that discharge near the ceiling level should be considered, to avoid spreading the gas plume.

LNG Vehicle Facilities. The 2006 edition of NFPA *Standard* 57 includes requirements for LNG bus facilities. The standard recommends a separate mechanical ventilation system providing at least 0.017 m^3/s per 12 m^3, or 5 ach, for indoor fueling areas. The ventilation system should operate continuously or be activated by a continuously monitoring natural gas detection system when a gas concentration of not more than 20% of the LFL is present. Fueling equipment should be interlocked to shut down in case the mechanical ventilation system fails. DOT (1997b) provides further information on LNG fuel.

LPG Vehicle Facilities. NFPA *Standard* 58 and the *International Fuel Gas Code*® (ICC 2009d) contain similar provisions relating specifically to LPG-fueled vehicles. Both standards prohibit indoor fueling of all LPG vehicles, allowing only an adequately ventilated weather shelter or canopy for fueling operations. However, the term "adequately ventilated" is not defined by any prescriptive rate. Vehicles are permitted to be stored and serviced indoors under NFPA *Standard* 58, provided they are not parked near sources of heat, open flames (or similar sources of ignition), or "inadequately ventilated" pits. That standard does not recommend a ventilation rate for bus repair and storage facilities, but it does recommend a minimum of 0.005 $m^3/(s \cdot m^2)$ in buildings and structures housing LPG distribution facilities. DOT (1996b) provides additional information on LPG fuel.

Hydrogen Vehicle Facilities. The 2006 edition of NFPA *Standard* 52 includes requirements for gaseous and liquid hydrogen bus facilities. The standard recommends a separate mechanical ventilation system providing at least 0.017 m^3/s per 12 m^3, but not less than 0.005 $m^3/(s \cdot m^2)$, or 5 ach, for indoor gaseous hydrogen fueling areas. The ventilation system should operate continuously or be activated by a continuously monitoring natural gas detection system when a gas concentration of not more than 25% of the LFL is present. Fueling equipment should be interlocked to shut down in case the mechanical ventilation system fails. Liquid hydrogen fueling facilities are prohibited indoors. The *International Mechanical*

Code® (ICC 2009a) has the same requirements, which apply to maintenance and repair areas as well as indoor fueling facilities.

DOT (1998) provides additional information on hydrogen fuel.

5. BUS TERMINALS

The physical configuration of bus terminals varies considerably. Most terminals are fully enclosed spaces containing passenger waiting areas, ticket counters, and some retail areas. Buses load and unload outside the building, generally under a canopy for weather protection. In larger cities, where space is at a premium and bus service is extensive or integrated with subway service, bus terminals may have comprehensive customer services and enclosed (or semienclosed) multilevel structures, busway tunnels, and access ramps. Waiting rooms and consumer spaces should have controlled environments in accordance with normal HVAC system design practices for public terminal occupancies. In addition to providing the recommended ventilation air rate in accordance with ANSI/ASHRAE *Standard* 62.1, the space should be pressurized against infiltration from the busway environment. Pressurized vestibules should be installed at each doorway to further reduce contaminant migration and to maintain acceptable air quality. Waiting rooms, passenger concourse areas, and platforms are typically subjected to a highly variable people load. The average occupant density may reach 1.0 m^2 per person and, during periods of extreme congestion, 0.3 to 0.5 m^2 per person.

The choice between natural and mechanical ventilation should be based on the physical characteristics of the bus terminal and the airflow required to maintain acceptable air quality. When natural ventilation is selected, the individual levels of the bus terminal should be open on all sides, and the slab-to-ceiling dimension should be sufficiently high, or the space contoured, to allow free air circulation. Jet fans can be used to improve natural airflow in the busway, with relatively low energy consumption. Mechanical systems that ventilate open platforms or gate positions should be configured to serve bus operating areas, as shown in Figures 18 and 19.

Platforms

Platform design and orientation should be tailored to expedite passenger loading and unloading, to minimize both passenger exposure to the busway environment and dwell time of an idling bus in an enclosed terminal. Naturally ventilated drive-through platforms may expose passengers to inclement weather and strong winds. An enclosed platform (except for an open front), with the appropriate mechanical ventilation system, should be considered. Partially enclosed platforms can trap contaminants and may require mechanical ventilation to achieve acceptable air quality.

Multilevel bus terminals have limited headroom, which restricts natural ventilation system performance. These terminals should have mechanical ventilation, and all platforms should be either partially or fully enclosed. The platform ventilation system should not induce contaminated airflow from the busway environment. Supply air velocity should also be limited to 1.3 m/s to avoid drafts on the platform. Partially enclosed platforms require large amounts of outdoor air to hinder fume penetration; experience indicates that a minimum of 0.086 $m^3/(s \cdot m^2)$ of platform area is typically required during rush hours, and about half this rate is required during other periods. Figure 18 shows a partially enclosed drive-through platform with an air distribution system.

Platform air quality should remain essentially the same as that of the ventilation air introduced. Because of the piston effect, however, some momentarily high concentrations of contaminants may occur on the platform. Separate ventilation systems with two-speed fans (for each platform) allow operational flexibility, in both fan usage frequency and supply airflow rate for any one platform. Fans should be controlled automatically to conform to bus operating schedules. In cold climates, mechanical ventilation may need to be reduced or heated during extreme winter weather conditions.

For large terminals with heavy bus traffic, fully enclosed platforms are strongly recommended. Fully enclosed platforms can be adequately pressurized and ventilated with normal heating and cooling air quantities, depending on the construction tightness and number of boarding doors and other openings. Conventional air distribution can be used; air should not be recirculated. Openings around doors and in the enclosure walls are usually adequate to relieve air pressure, unless the platform construction is extraordinarily tight. Figure 19 shows a fully enclosed waiting room with sawtooth gates.

Doors between sawtooth gates and the waiting room should remain closed, except for passenger loading and unloading. The waiting room ventilation system should provide positive pressurization to minimize infiltration of contaminants from the busway environment. Supply air from a suitable source should be provided at the passenger boarding area to dilute local contaminants to acceptable levels.

Bus Operation Areas

Ventilation for bus operation areas should be designed and evaluated to maintain engine exhaust contaminant concentrations within the limits set by federal and local regulations and guidelines. With the proliferation of alternative fuels, such as biodiesel, ethanol, methanol, compressed natural gas (CNG), and liquefied natural gas (LNG), a bus terminal ventilation system should not only be designed for maintaining acceptable air quality, but should also consider the safety risks associated with potential leakage from buses operating with alternative fuel loads. In an enclosed or semienclosed area, a comprehensive risk assessment should be performed for the specific types of buses operating in the bus terminal. The nature of the bus engines should be determined for each project.

Contaminants. Of all the different types of buses in operation, engine exhaust from diesel buses has the most harmful quantities of contaminants. Some diesel buses also have small auxiliary gasoline engines to drive the vehicle air-conditioning system. Excessive exposure to diesel exhaust can cause adverse health effects, ranging from headache and nausea to cancer and respiratory disease. Tests on the volume and composition of exhaust gases emitted from diesel engines during various traffic conditions indicate large variations depending on the (1) local air temperature and

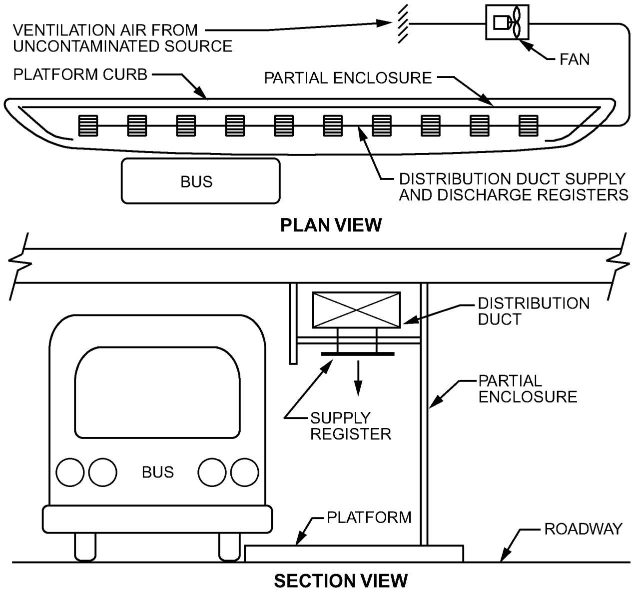


Fig. 18 Partially Enclosed Platform, Drive-Through Type

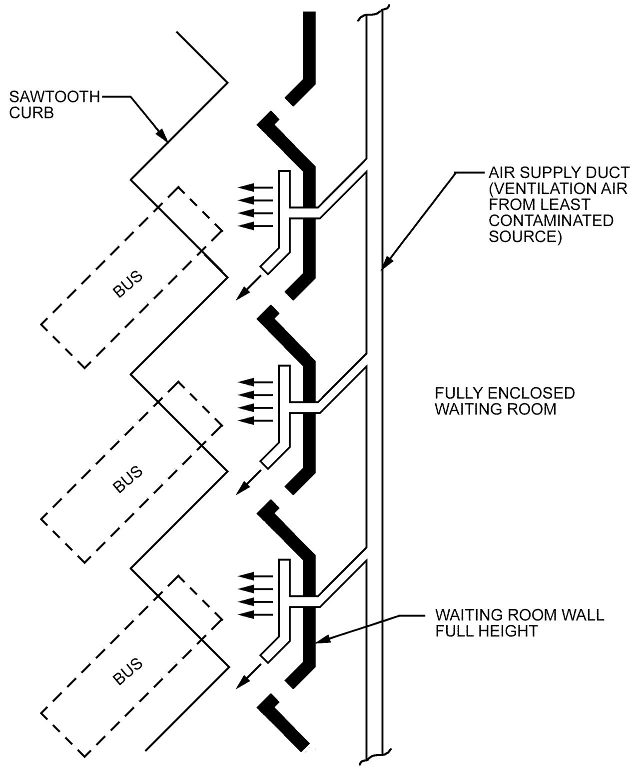


Fig. 19 Fully Enclosed Waiting Room with Sawtooth Gates

humidity; (2) manufacturer, size, and adjustment of the engine; and (3) type of fuel used.

Components of diesel engine exhaust gases that affect the ventilation system design are NO_x, hydrocarbons, formaldehyde, odor constituents, aldehydes, smoke particles, sulfur dioxide, and a relatively small amount of CO. Diesel engines operating in enclosed spaces also reduce visibility, and generate both odors and particulate matter.

Table 9 lists major health-threatening contaminants found in diesel engine exhaust and the exposure limits set by OSHA and ACGIH.

OSHA permissible exposure limits (PEL) are legally enforceable limits, whereas the ACGIH threshold limit values (TLV) are industrial hygiene recommendations. All the limits are time-weighted averages (TWAs) for 8 h exposure, unless noted as a ceiling value.

NO_x occurs in two basic forms: nitrogen dioxide (NO_2) and nitric oxide (NO). NO_2 is the major contaminant considered in bus terminal ventilation system design. Prolonged exposure to NO_2 concentrations of more than 5 ppm causes health problems. Furthermore, NO_2 affects light transmission and thereby reduces visibility. NO_2 is intensely colored and absorbs light over the entire visible spectrum, especially at shorter wavelengths. Odor perception of NO_2 is immediate at 0.42 ppm, but can be perceived by some at levels as low as 0.12 ppm.

Bus terminal operations also affect the quality of surrounding ambient air. The ventilation airflow rate, contaminant levels in exhaust air, and location and design of the air intakes and discharges determine the effect of the bus terminal on local ambient air quality.

State and local regulations, which require consideration of local atmospheric conditions and ambient contaminant levels in bus terminal ventilation system design, must be followed.

Table 9 8 h TWA Exposure Limits for Gaseous Pollutants from Diesel Engine Exhaust, ppm

Substance	OSHA PEL	ACGIH TLV
Carbon monoxide (CO)	50	25
Carbon dioxide (CO_2)	5000	5000
Nitric oxide (NO)	25	25
Nitrogen dioxide (NO_2)	5.0*	3.0
Formaldehyde (HCHO)	0.75	0.30*
Sulfur dioxide (SO_2)	5	2.0

*Ceiling value

Note: For data on diesel bus and truck engine emissions, see Watson et al. (1988).

Table 10 EPA Emission Standards for Urban Bus Diesel Engines

	Emissions, g/(h·kW)			
Model Year	Hydrocarbons (HC)	Carbon Monoxide (CO)	Oxides of Nitrogen (NO_x)	Particulate Matter (PM)
1991	1.74	20.8	6.72	0.335
1993	1.74	20.8	6.72	0.135
1994	1.74	20.8	6.72	0.094
1996	1.74	20.8	6.72	0.067*
1998 to 2003	1.74	20.8	5.37	0.067*
2004 to 2006	1.74	20.8	2.68 to 3.35	0.067*
2007 and later	0.198	20.8	0.027	0.014

*In-use PM standard 0.094 g/(h·kW)

Calculation of Ventilation Rate

To calculate the ventilation rate, the total amount of engine exhaust gases should be determined using the bus operating schedule and amount of time that the buses are in various modes of operation (i.e., cruising, decelerating, idling, and accelerating). The designer must ascertain the grade (if any) in the terminal, and whether platforms are drive-through, drive-through with bypass lanes, or sawtooth. Bus headway, bus speed, and various platform departure patterns must also be considered. For instance, with sawtooth platforms, the departing bus must accelerate backward, brake, and then accelerate forward. The drive-through platform requires a different pattern of departure.

Certain codes prescribe a maximum idling time for bus engines, usually 3 to 5 min. Normally, 1 to 2 min of engine operation is required to build up brake air pressure. EPA emission standards for urban bus engines are summarized in Table 10 (bus emission standards in the state of California are more restrictive). The latest version of the EPA emission factor algorithm should be used to estimate bus tailpipe emissions. MOBILE6.2 (EPA 2002) has been replaced by MOVES2010 (EPA 2009, 2010). Input parameters (e.g., local vehicular inspection and maintenance requirements) suitable for a specific facility should be obtained from the appropriate air quality regulatory agency.

Discharged contaminant quantities should be diluted by natural and/or mechanical ventilation to accepted, legally prescribed levels. To maintain odor control and visibility, exhaust gas contaminants should be diluted with outdoor air in the proportion 75 to 1.

Where urban-suburban bus operations are involved, the ventilation rate varies considerably throughout the day and also between weekdays and weekends. Fan speed or blade pitch control should be used to conserve energy. The required ventilation airflow may be reduced by removing contaminant emissions as quickly as possible. This can be achieved by mounting exhaust capture hoods in the terminal ceiling, above each bus exhaust stack. Exhaust air collected by the hoods is then discharged outside of the facility through a dedicated exhaust system.

Effects of Alternative Fuel Use. As discussed in the section on Bus Garages, alternative fuels are being used more widely in lieu of conventional diesel fuel, especially for urban-suburban bus routes, as opposed to long-distance bus service.

Current codes and design standards developed for conventional fuels may not be valid for alternative-fuel buses. Comprehensive design guidelines are not yet available; there is a lack of design standards and long-term safety records for the alternative-fuel buses and their components. Special attention should be given to both risk assessment and design of HVAC and electrical systems for these facilities with regard to a fuel tank or fuel line leak. Research is continuing in this application; further information may be available from the DOT Volpe Transportation Center and NFPA *Standards* 52 and 58.

Bus terminal design should include a risk assessment to review terminal operations and identify potential hazards from alternative fuel buses. Facility managers should adopt safety principles to determine the acceptability of these hazards, based on severity and frequency of occurrence. All hazards deemed undesirable or unacceptable should be eliminated by system design or by modifications to operations.

Natural Gas (NG) Buses. Fuel burned in LNG and CNG buses has a composition of up to 98% methane (CH_4). Methane burns in a self-sustained reaction only when the volume percentage of fuel and air is in specific limits. The lower and upper flammability, or explosive, limits (LEL and UEL) for methane are 5.3% and 15.0% by volume, respectively. At standard conditions, the fuel/air mixture burns only in this range and in the presence of an ignition source, or when the spontaneous ignition temperature of 540°C is exceeded.

Electrical and mechanical systems in a bus terminal facility should be designed to minimize the number of ignition sources at locations where an explosive natural gas mixture can accumulate.

Although emissions from an NG bus engine include unburned methane, design of the bus terminal ventilation system must be based on maintaining facility air quality below the LEL in the event of a natural gas leak. A worst-case scenario for natural gas accumulation in a facility is a leak from the bus fuel line or fuel tank, or a sudden high-pressure release of natural gas from a CNG bus fuel tank through its pressure relief device (PRD). For instance, a typical CNG bus may have multiple fuel tanks, each holding gas at 25 MPa and 21°C. If the PRD on a single tank were to open, the tank contents would escape rapidly. After 1 min, 50% of the fuel would be released to the surroundings, after 2 min, 80% would be released, and 90% would be released after 3 min.

Because such a large quantity of fuel is released so quickly, prompt activation of a ventilation purge mode is essential. Where installed, a methane detection system should activate a ventilation purge and an alarm at 20% of the LEL. Placement of methane detectors is very important; stagnant areas, bus travel lanes, and bus loading areas must be considered. In addition, although methane is lighter than air (the relative density of CH_4 is 0.55), some research indicates that it may not rise immediately after a leak. In a natural gas release from a PRD, the rapid throttle-like flow through the small-diameter orifice of the device may actually cool the fuel, making it heavier than air. Under these conditions, the fuel may migrate toward the floor until reaching thermal equilibrium with the surrounding environment; then, natural buoyancy forces drive the fuel/air mixture to the ceiling. Thus, the designer may consider locating methane detectors at both ceiling and floor levels of the facility.

Although no specific ventilation criteria have been published for natural gas vehicles in bus terminals, NFPA *Standard* 52 recommends a blanket rate of 5 ach in fueling areas. DOT (1996a) guidelines for CNG transit facility design recommend a slightly more conservative 6 ach for normal ventilation rates in bus storage areas, with capability for 12 ach ventilation purge rate (on activation by the methane sensors). The designer can also calculate a ventilation purge rate based on the volumetric flow rate of methane released, duration of the release, and size of the facility.

The size of the bus terminal significantly affects the volume flow of ventilation air required to maintain the average concentration of methane below 10% of the LEL. The larger the facility, the lower the number of air changes required. However, a methane concentration that exceeds the LEL can be expected in the immediate area of the leak, regardless of the ventilation rate used. The size of the plume and location/duration of the unsafe methane concentration may be determined using comprehensive modeling analysis, such as computational fluid dynamics.

Source of Ventilation Air. Because dilution is the primary means of contaminant level control, the ventilation air source is extremely important. The cleanest available ambient air should be used for ventilation; in an urban area, the cleanest air is generally above roof level. Surveys of contaminant levels in ambient air should be conducted, and the most favorable source of ventilation air should be used. The possibility of short-circuiting exhaust air, because of prevailing winds and/or building airflow patterns, should also be evaluated.

If the only available ambient air has contaminant levels exceeding EPA ambient air quality standards, the air should be treated to control offending contaminants. Air-cleaning systems for removing gases, vapors, and dust should be installed to achieve necessary air quality.

Control by Contaminant Level Monitoring. Time clocks are one of the most practical means of controlling a bus terminal ventilation system. Time-clock-based ventilation control systems are typically coordinated with both bus movement schedules and installed smoke monitoring devices (i.e., obscurity meters). A bus terminal ventilation system can also be controlled by monitoring levels of individual gases, such as CO, CO_2, NO_2, methane, or other toxic or combustible gases.

Dispatcher's Booth. The bus dispatcher's booth should be kept under positive air pressure to prevent infiltration of engine exhaust fumes. Because the booth is occupied for sustained periods, both normal interior comfort conditions and minimized gas contaminant levels must be maintained during the hours of occupancy.

6. TOLLBOOTHS

Toll plazas for vehicular tunnels, bridges, and toll roads generally include a series of individual tollbooths. An overhead weather canopy and a utility tunnel (located below the roadway surface) are frequently provided for each toll plaza. The canopy allows installation of roadway signs, air distribution ductwork, and lighting. The utility tunnel is used to install electrical and mechanical systems; it also provides access to each tollbooth. An administration building is usually situated nearby. The current trend in toll collection facility design favors automatic toll collection methods that use magnetic tags. However, new and retrofit toll plazas still include a number of manual toll collection lanes with individual tollbooths.

Toll collectors and supervisors are exposed to adverse environmental conditions similar to those in bus terminals and underground parking garages. Automotive emission levels are considerably higher at a toll facility than on a highway because of vehicle deceleration, idling, and acceleration. Increased levels of CO, NO_x, diesel particulates, gasoline fumes, and other automotive emissions have a potentially detrimental effect on health.

Toll collectors cannot totally rely on physical barriers to isolate them from automotive emissions, because open windows are necessary for collecting tolls. Frequent opening and closing of the window makes the heating and cooling loads of each booth fluctuate independently. Heat loss or gain is extremely high, because all four sides (and frequently the ceiling) of the relatively small tollbooth are exposed to the outdoor ambient air temperature.

HVAC air distribution requirements for a toll facility should be carefully evaluated to maintain an acceptable environment inside the tollbooth and minimize the adverse ambient conditions to which toll-collecting personnel are exposed.

Air Quality Criteria

Workplace air quality standards are mandated by local, state, and federal agencies. Government health agencies differ on acceptable CO levels. ACGIH (1998) recommends a threshold limit of 29 mg/m^3 (25 ppm) of CO for an 8 h exposure. OSHA (2001a) regulations are for 55 mg/m^3 (50 ppm) for repeated daily 8 h exposure to CO in the ambient air. The U.S. National Institute for Occupational Safety and Health (NIOSH 1994) recommends maintaining an average of 40 mg/m^3 (35 ppm) and a maximum level of 230 mg/m^3 (200 ppm). Criteria for maximum acceptable CO levels should be developed with the proper jurisdiction. As a minimum, the ventilation system should be designed to maintain CO levels below the threshold limit for an 8 h exposure. Deceleration, idling, and acceleration of vehicles, and varying traffic patterns make it difficult to estimate CO levels around specific toll-collecting facilities without using computer programs.

Longitudinal tunnel ventilation systems with jet fans or Saccardo nozzles are increasingly popular for vehicular tunnels with unidirectional traffic flow. These longitudinal ventilation systems discharge air contaminants from the tunnel through the exit portal. If toll plazas are situated near the exit portal, resultant CO levels around the facilities may be higher than for other toll facilities.

If a recirculating HVAC system were used for a toll collection facility, any contaminants entering a particular tollbooth would remain in the ventilation air. Therefore, tollbooth ventilation systems should distribute 100% outdoor air to each booth to prevent both intrusion and recirculation of airborne contaminants.

Design Considerations

The toll plaza ventilation system should pressurize booths to keep out contaminants emitted by traffic. Opening the window during toll collection varies depending on booth design and the habits of the individual toll collector. The amount of ventilation air required for pressurization similarly varies.

Variable-air-volume (VAV) systems that are achievable with controls now available can vary the air supply rate based on either the pressure differential between the tollbooth and the outdoor environment, or the position of the tollbooth window. A fixed (maximum/minimum) volume arrangement may also be used at toll plazas with a central VAV system.

Because the area of the window opening varies with individual toll collector habits and booth architecture, the design air supply rate may be determined based on an estimated average window open area. The minimum air supply (when the booth window is closed) should be based on the amount of air required to meet the heating/cooling requirements of the booth and that required to prevent infiltration of contaminants through the door and window cracks. Where the minimum supply rate exceeds the exfiltration rate, provisions to relieve excess air should be made to prevent overpressurization.

The space between the booth roof and the overhead canopy may be used to install individual HVAC units, fan-coil units, or VAV boxes. Air ducts and HVAC piping may be installed on top of the plaza canopy or in the utility tunnel. The ducts or piping should be insulated as needed.

The amount of ventilation air is typically high compared to the size of the booth; the resulting rate of air change is also high. Supply air outlets should be sized and arranged to deliver air at low velocity. Air reheating should be considered where the supply air temperature is considered too low.

In summer, the ideal air supply location is the ceiling of the booth, which allows cooler air to descend through the booth. In winter, the ideal air supply location is from the bottom of the booth, or at floor level. It is not always possible to design ideal distribution for both cooling and heating. When air is supplied from the ceiling, other means for providing heat at floor level (e.g., electric forced-air heaters, electric radiant heating, heating coils in the floor) should be considered.

The supply air intake should be located so that air drawn into the system is as free as practicable of vehicle exhaust fumes. The prevailing wind should be considered when locating the intake, which should be as far from the roadway as is practicable to provide better-quality ventilation air. Particle filtration of supply air for booths should be carefully evaluated. The specific level and type of filtering should be based on the ambient level of particulate matter and the desired level of removal. See Chapter 11 of the 2013 *ASHRAE Handbook—Fundamentals* and Chapter 29 in the 2012 *ASHRAE Handbook—HVAC Systems and Equipment* for more information.

Equipment Selection

Individual HVAC units and central HVAC are commonly used for toll plazas. Individual HVAC units allow each toll collector to choose between heating, cooling, or ventilation modes. Maintenance of individual units can be performed without affecting HVAC units in other booths. In contrast, a central HVAC system should have redundancy to avoid a shutdown of the entire toll plaza system during maintenance operations.

The design emphasis on booth pressurization requires using 100% outdoor air; high-efficiency air filters should therefore be considered. When a VAV system is used to reduce operating cost, varying the supply rate of 100% outdoor air requires a complex temperature control system that is not normally available for individual HVAC units. Individual HVAC units should be considered only where the toll plaza is small or where the tollbooths are so dispersed that a central HVAC system is not economically justifiable.

Where hot-, chilled-, or secondary water service is available from an adjacent administration building, an individual fan-coil for each tollbooth and a central air handler for supplying the total volume of ventilation air may be economical. When the operating hours for the booths and administration building are significantly different, separate heating and cooling for the toll-collecting facility should be considered. Central air distribution system selection should be based on the maximum number of open traffic lanes during peak hours and the minimum number of open traffic lanes during off-peak hours.

The HVAC system for a toll plaza is generally required to operate continuously. Minimum ventilation air may be supplied to unoccupied tollbooths to prevent infiltration of exhaust fumes. Otherwise, consideration should be given to remotely flushing the closed tollbooths with ventilation air before their scheduled occupancy.

7. DIESEL LOCOMOTIVE FACILITIES

Diesel locomotive facilities include shops where locomotives are maintained and repaired, enclosed servicing areas where supplies are replenished, and overbuilds where locomotives routinely operate inside an enclosed space and where railroad workers and/or train passengers may be present. In general, these areas should be kept under slightly negative air pressure to help removal of fumes and contaminants. Ventilation should use 100% outdoor air. However, recirculation may be used to maintain space temperature when a facility is unoccupied or when engines are not running. Heat recovery devices should be considered for facilities in colder climates, though they may require additional maintenance.

Historically, ventilation guidelines for locomotive facilities have recommended simple exhaust rates usually based on the volume of the facility. These were developed over many years of experience and were based on the assumption of nitrogen dioxide as the most critical contaminant. Because contaminant limits for constituents of diesel exhaust have been and are likely to continue changing, ASHRAE sponsored research project RP-1191 (Musser and Tan 2004), which included field measurements in several facilities and a parametric study of design options using computational fluid dynamics. The study resulted in a simplified contaminant-based design procedure that allows designers flexibility to adapt to other critical contaminants or concentrations. Both the traditional and RP-1191 approaches are discussed here.

Ventilation Guidelines and Facility Types

Maintenance and Repair Areas. ANSI/ASHRAE *Standard* 62.1 and most model codes require a minimum outdoor air ventilation rate of 0.0075 $m^3/(s \cdot m^2)$ in vehicle repair garages, with no recirculation recommended. Because the ceiling is usually high in locomotive repair shops, the designer should consider making a volumetric analysis of contaminant generation and air exchange rates rather than using the 0.0075 $m^3/(s \cdot m^2)$ ventilation rate as a blanket standard. The sections on Contaminant Level Criteria and Contaminant Emission Rate have more information on diesel engine exhaust emissions.

Information in the section on Bus Garages also applies to locomotive shops, especially for below-grade pits, battery charging areas, and paint spray booths. However, diesel locomotives generally have much larger engines (ranging to over 4500 kW) than buses. Ventilation is needed to reduce crew and worker exposure to exhaust gas contaminants, and to remove heat emitted from engine radiators. Where possible, diesel engines should not be operated in shops. Shop practices should restrict diesel engine activity and engine operating speeds/intervals; however, some shops require that locomotives be load-tested at high engine speeds. This should be done outdoors if possible, both to reduce indoor contaminants and to avoid problems associated with high heat (sprinkler activation, fire risk, etc.).

A dedicated area should be established for diesel engine operations; hoods should be used to capture engine exhaust in this area. If hoods are impractical because of physical obstructions, then dilution ventilation must be used.

In designing hoods, the location of each exhaust point on each type of locomotive must be identified so that each hood can be centered and located as close as possible to each exhaust point. Local and state railroad clearance regulations must be followed, along with occupational safety requirements. In some cases, high ceilings or overhead cranes may limit hood use. Some newer systems attempt to avoid this problem by using a flexible connection that attaches to the exhaust.

The hood design should not increase backpressure on locomotive exhaust; the throat velocity should be kept less than twice the exhaust discharge velocity. The associated duct design should include access doors and provisions for cleaning oily residue, which increases the risk of fire. Fans and other ventilation equipment in the airstream should be selected with regard to the elevated temperature of the exhaust air and the effects of the oily residue in the emissions.

Sometimes high ceilings or overhead cranes limit the use of hoods. The *Manual for Railway Engineering* (AREMA 2007) notes that 6 air changes per hour are usually sufficient to provide adequate dilution for both idling locomotives and short engine runs at high speed. This guideline was developed with nitrogen dioxide as the critical contaminant, with an allowable maximum concentration of 5 ppm(v). Even dilution systems can and should take advantage of thermal buoyancy by removing exhaust air at the ceiling level or a high point in the shop and introducing makeup air at floor level. If exhaust gases are allowed to cool and drop to floor level, locomotive radiator fans (if operating) can cause further mixing in the occupied zone, making removal less effective.

Shops in colder climates should be heated both for worker comfort and to prevent freezing of facility equipment and piping. The heating system may consist of a combination of perimeter convectors to offset building transmission losses, underfloor slab or infrared radiation for comfort, and makeup air units for ventilation. Where natural gas is available and local codes allow, direct-fired gas heaters can be an economical compromise to provide a high degree of worker comfort. Air curtains or door heaters are not needed in shops where doors are opened infrequently.

Enclosed Servicing Areas. Although most locomotive servicing is done outdoors, some railroads use enclosed servicing areas for protection from weather and extreme cold. Servicing operations include refilling fuel tanks, replenishing sand (used to aid traction), draining toilet holding tanks, checking lubrication oil and radiator coolant levels, and performing minor repairs. Generally, a locomotive spends less than 1 h in the servicing area. Ventilation is needed to reduce personnel exposure to exhaust gas contaminants and remove heat emitted from engine radiators. The designer should also consider the presence of vapors from fuel oil dispensing and silica dust from sanding. Heating may also be included in the design, depending on the need for worker comfort and the operations performed.

Ventilation for servicing areas should be similar to that for maintenance and repair areas. Where possible, hoods should be used in lieu of dilution ventilation. However, coordinating hood locations with engine exhaust points may be difficult because different types of locomotives may be coupled together in consists. Elevated sanding towers and distribution piping may also interfere. Contaminant levels might be higher in servicing areas than in the shops because of constantly idling locomotives and occasional higher-speed movements in servicing areas. For dilution ventilation, the designer should ascertain the type of operations planned for the facility and make a volumetric analysis of expected rates of contaminant generation and air exchange.

Infrared radiation should be considered for heating. As with maintenance and repair areas, direct-fired gas heaters may be economical. Door heaters or air curtains may be justified because of frequent opening of doors or a lack of doors.

Overbuilds. With increasing real estate costs, the space above trackways and station platforms is commonly built over to enclose the locomotive operation area. Ventilation is needed in overbuilds to reduce crew and passenger exposure to exhaust gases and to remove heat emitted from engine radiators and vehicle air-conditioning systems. Overbuilds are generally not heated.

Exhaust emissions from a diesel passenger locomotive operating in an overbuild are higher than from an idling locomotive because of head-end power requirements. The designer should determine the types of locomotives to be used and the operating practices in the overbuild. As with locomotive repair shops and servicing areas, hoods are recommended to capture engine exhaust. According to the *Overbuild of Amtrak Right-of-Way Design Policy* (Amtrak 2005), the air temperature at the exhaust source will be between 175 and 510°C. A typical ventilation design could have hoods approximately 5.5 to 7 m above the top of the rail, with throat velocities between 9 and 11 m/s. For dilution ventilation, the designer should perform a volumetric analysis of contaminant generation and air exchange rates.

Contaminant Level Criteria

In most locations, diesel exhaust is not regulated specifically, although concentrations of many substances found in diesel exhaust are regulated. The U.S. Occupational Safety and Health Administration (OSHA 2001a, 2001b) identifies carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), nitric oxide (NO), diesel particulate matter (DPM), and sulfur dioxide (SO_2) as major components of diesel exhaust. Thirty-one additional substances are identified as minor components, with seventeen of these being polycyclic aromatic hydrocarbons (PAH). These minor components are elements of DPM.

Federal OSHA requirements establish limits for these compounds in the United States, although a few states may set more restrictive requirements. Also, the American Council of Governmental and Industrial Hygienists (ACGIH) publishes guideline values for use in industrial hygiene that are not legally enforceable, but may evolve more quickly than OSHA requirements (ACGIH 2001). Other countries set their own contaminant limits, though these may draw heavily from the ACGIH and other U.S. publications.

When no regulations exist for DPM, nitrogen dioxide (NO_2) is present in diesel exhaust emissions at the highest levels relative to its published limits. In these circumstances, systems designed to control nitrogen dioxide will maintain other exhaust-related contaminants well below their respective limits. Table 11 shows published exposure limits in parts per million (ppm). Federal OSHA, ACGIH, and NIOSH limits are current as of at least February 2003. Other limits are taken primarily from an international database of participating countries (ILO 2003; Lu 1993). Contaminant limits are often expressed in mg/m^3, even in regions where I-P units are used.

Most authorities do not currently distinguish DPM from other particulates; however, this may change. The ACGIH added DPM measured as elemental carbon to its TLVs (ACGIH 2003). A 0.1 mg/m^3 limit for elemental carbon in diesel environments has been established in Germany. Laws enacted by the Mine Safety and Health Administration are targeted toward limiting DPM in mining environments (MSHA 2001a, 2001b). These changes may foreshadow action by OSHA. In this changing environment, designers must check local regulations in the time and place of construction for applicable limits.

Contaminant Emission Rate

Locomotive contaminant emissions have been measured primarily for environmental reasons, and data for some models have been published in the environmental literature (Table 12). These data are classified for different duty-cycles of operation and different throttle settings, and were obtained from controlled tests conducted under steady-state operation. Engine speed, engine power, fuel rate, and engine airflow are typically reported. Emissions are usually reported for carbon monoxide (CO), oxides of nitrogen (NO_x), hydrocarbons, sulfur dioxide (SO_2), and particulates. Manufacturers can provide this information for specific engine models and should be consulted for current and specific data for design projects.

Note that passenger locomotives consume a greater amount of power when idling with head-end power (HEP) to serve passenger-related needs. A passenger train idle at HEP can produce five times the amount of NO_x emissions as the same train idling with no HEP effects (Fritz 1994). Thus, this is an important distinction between passenger railway stations, where HEP is likely to be required, and repair facilities, where HEP is not likely to be needed.

Available emissions data have been targeted toward outdoor pollution concerns, which imposes some limitations in applying it to indoor settings. Only recent tests document exhaust temperatures, a quantity useful to design engineers concerned with sprinkler systems. Emissions data come from steady-state tests on engines whose operation has been allowed to stabilize for an hour or more, so a safety factor is suggested to allow for higher emissions related to cold start and transient operation. Also, the data include only a combined NO_x emissions value. Field measurements in locomotive facilities found that about 13% (by mass) of ambient NO_x could be attributed to NO_2 (Musser and Tan 2004). This factor can be used estimate NO_2 source emissions from available data. The applicability of these data to design applications is supported by comparisons of CFD models based on published emissions data and field measurements taken in repair shops that showed reasonable agreement between the measured and predicted values (Musser and Tan 2004).

Table 11 Contaminant Exposure Limits for NO_2

(For information only; check updated local regulations)

	NO_2, mg/m^3		
Entity	**8 h**	**15 min**	**Ceiling**
OSHA: USA (PEL)			9
ACGIH: USA (TLV)	6	9	
NIOSH: USA (REL)		2	
Australia	6	9	
Belgium	6	9	
Denmark	6	9	
Finland	6	11	
France		6	
Germany			9
Japan			
Sweden	2*		
Switzerland	6	11	
United Kingdom	6	9	
China			5

*Limit specifically for NO_2 from exhaust fumes.

Locomotive Operation

Designers need to anticipate locomotive operation during the design phase, particularly when estimating source strength based on published locomotive emissions data. Some important parameters include the number of operating locomotives and the location, duration, and throttle position at which they operate. The number of locomotives likely to be operating can be estimated based on shop or station schedules. Although it is important to remember that a locomotive could idle at any location inside a facility, there are often practical cues to identify the most common or likely locations. These include platforms, facility layout, location of equipment for servicing toilets, fuel stations, or other service equipment. In small shops, the layout may create one or two convenient positions in which locomotives are very likely to be parked.

Other operating parameters may be more difficult to estimate, particularly in shops. Field observations for ASHRAE research project RP-1191 recorded locomotive operation in several shops varying from a few minutes to an hour in duration, usually at idle and low throttle settings (Musser and Tan 2004). Operation was influenced by shop rules, practices, and conventions, which are valuable to consider during the design phase. The cooperation and involvement of shop employees in the design stage can help integrate these practices so that the design conforms to the needs of the facility, rather than the other way around.

Design Methods

General Exhaust Systems. A contaminant-based procedure using a simplified equation developed with computational fluid dynamics can be used to design general exhaust systems using the steps below. The simplified equation was developed to flexibly adapt to changes in contaminant limits. Figures 20 and 21 show schematic drawings of such a system.

Step 1: Verify that design parameters to be used in the simplified equation fall within the ranges for which the equation is valid.

- Ceiling height Z must be 6 to 13.7 m.
- Fan spacing X must be 6 to 18 m.
- Exhaust fan flow Q must provide 5 to 12 air changes per hour (ach).

Step 2: Verify that other facility characteristics show reasonable agreement with the assumptions of the parametric study:

Table 12 Sample Diesel Locomotive Engine Emission Data[a]

Throttle Position (Notch)	Engine Speed, rpm	Engine Power, kW	Engine Airflow,[b] m^3/s	Fuel Rate, kg/h	NO_x, g/min	CO, g/min	HC, g/min	SO_2, g/min	Particulates, g/min
Four-Stroke Cycle, With Head End Power (HEP)									
8, Freight	1050	2437	4.161	500	612	45	29	3.8	7.2
7, HEP	900	2066	3.336	421	540	95	23	3.2	8.1
6, HEP	900	1681	2.675	346	471	87	20	2.7	7.0
5, HEP	900	1325	2.092	276	386	76	12	2.1	4.9
4, HEP	900	763	1.263	167	253	25	9.1	1.3	3.9
3, HEP	900	532	0.970	121	170	18	7.1	0.93	3.7
2, HEP	900	321	0.782	79	109	12	6.6	0.60	4.1
1, HEP	900	240	0.779	65	96	12	6.9	0.50	4.9
HEP idle	900	138	0.713	37	48	15	8.3	0.28	6.9
Standby	720	382	0.680	86	118	14	6.2	0.65	5.0
High idle	450	25	0.220	10	15	3.7	3.0	0.08	1.0
Low idle	370	16	NA[c]	8	8.6	5.3	2.7	0.07	0.78
Two-Stroke Cycle, No Head End Power (HEP)									
8	903	2394	4.2	481	647	61	15	3.7	11
7	821	1894	3.4	378	424	31	9.3	2.9	7.3
6	726	1268	2.5	259	290	11	6.4	2.0	4.9
5	647	1037	2.2	218	248	10	6.0	1.7	4.4
4	563	790	1.9	167	213	4.6	4.8	1.3	3.2
3	489	532	1.6	115	178	3.2	3.9	0.88	2.3
2	337	276	1.0	64	100	3.5	2.5	0.50	0.90
1	337	154	1.1	41	58	2.6	1.9	0.32	0.50
High idle	339	10	1.1	15	19	1.3	1.6	0.12	0.40
Low idle	201	7	0.62	6	9.9	0.60	0.58	0.05	0.13
Auxiliary Engine/Alternator for Head End Power (HEP)									
N/A	1800	521	0.91	125	127	55	5.3	1.0	2.8
N/A	1800	422	1.0	103	129	8.2	5.9	0.78	NA[c]
N/A	1800	327	0.95	81	97	4.0	5.1	0.62	2.0
N/A	1800	281	0.90	71	78	3.0	4.6	0.55	1.9
N/A	1800	227	0.85	61	63	3.0	4.3	0.47	1.7
N/A	1800	177	0.81	52	49	3.0	4.3	0.40	1.5
N/A	1800	129	0.77	43	36	3.1	4.1	0.33	1.3
N/A	1800	23	0.70	25	17	3.5	4.6	0.20	1.2

[a] Data from Southwest Research Institute (SwRI 1992).
[b] Intake, corrected to standard air density 1.203 kg/m^3.
[c] Data not available.

- Fan dimensions *L*: Exhaust fan or duct dimensions are 1.5 by 1.5 m.
- Fan placement: Exhaust fans or duct openings are centered above each track.
- Locomotive exhaust temperature *T*: 177°C.
- Locomotive exhaust flow rate *F*: 1 m^3/s.
- Radiator fans: For many locomotive models, radiator fans do not operate when the locomotive is idling, and no radiator fan flow was modeled in this study. If radiator fans will be operating, they may alter the indoor airflow patterns.
- Operating time: The equation is based on steady state conditions, so it is not necessary to assume a maximum operating time.
- Concurrent operation: The equation allows for concurrent operation on different tracks. However, it does not include concurrent operation of more than one locomotive on the same track.
- Track-to-track spacing *Y*: 7.6 m.
- Ambient temperature: 32°C. This was selected because warmer ambient temperatures tend to reduce the upward buoyancy of warm exhaust gases.

Step 3: Obtain emissions data for critical contaminants and determine the design indoor concentration limit for the critical contaminant.

- Emissions data for some locomotive models are published in the environmental literature, and data for specific locomotives can be obtained from the manufacturer. The emissions rate for a given locomotive model depends on throttle position and whether head-end power is used.

Table 13 Constants for Equation (20)

Constant	No Platform	With 1.7 m Platform
a	20.0	22.5
b	–0.551	–0.773
c	–3.32	–2.09
d	–0.106	–0.109
e	–0.308	–0.346
f	0.0119	0.0159
g	0.235	0.236
h	0.0792	0.0407
i	0.00191	0.00190
j	–0.00505	–0.00499

- Acceptable indoor concentration limits can be determined from legal requirements at the location and time of construction. The designer may also wish to consider recommended limits from organizations such as ACGIH. To allow a safety margin, a designer might choose a contaminant limit that is lower than the published legal limit.

Contaminant limits are often expressed in mg/m^3, even in regions where I-P units are used. A contaminant limit in ppm(v) can

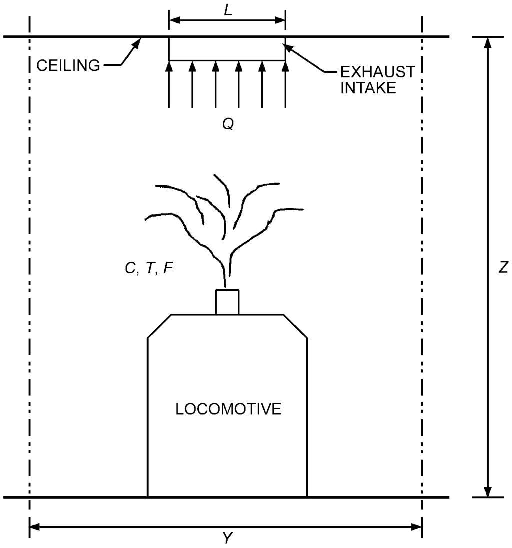


Fig. 20 Section View of Locomotive and General Exhaust System

be converted to mg/m^3 for use in the simplified equation as follows (ASHRAE *Standard* 62.1):

$$\text{ppm(v)} \times \frac{\text{Molecular mass}}{24.45} = \text{mg/m}^3 \tag{19}$$

Step 4: Select a fan flow rate and calculate the maximum concentration to which occupants would be exposed using Equation (20). Table 13 gives values for constants *a* to *j* whether occupants will be standing on the floor or a 1.2 m high platform.

$$C_{occ} = 10^{-3} C_{emissions}(a + bQ + cP + dX + eZ + fQZ + gPX + hPZ + iXZ + jPXZ) \tag{20}$$

where

C_{occ} = maximum time-averaged concentration of critical contaminant to which occupants could be exposed, mg/m^3
$C_{emissions}$ = concentration of critical contaminant in exhaust emissions, mg/m^3
a to j = constants found in Table 13
Q = total exhaust fan flow rate required, ach; must be between 5 and 12 ach
Z = ceiling height; must be 6 to 13.7 m
X = fan spacing; must be 6 to 18 m
P = locomotive offset position, dimensionless; $P = 0$ under fan and $P = 1$ between fans. Other values for P can be calculated based on the distance of locomotive stack from the nearest exhaust fan d and fan spacing X:

$$P = 2\frac{d}{X} \tag{21}$$

Step 5: Compare C_{occ} obtained in step 4 with the concentration limit C_{limit} determined in step 3. If $C_{occ} < C_{limit}$, the selected flow rate is adequate. If $C_{occ} > C_{limit}$, repeat step 4 with a higher flow rate until a concentration less than the limit is obtained.

Step 6: Verify that the result is between 5 and 12 ach.

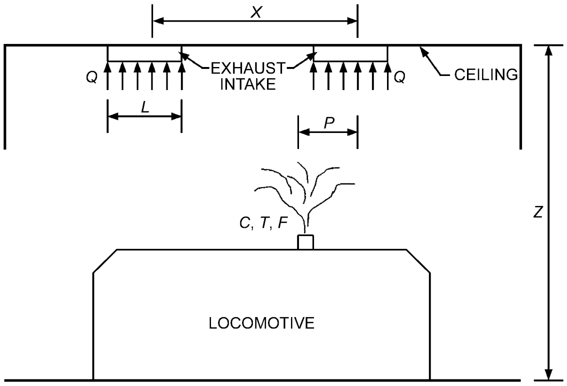


Fig. 21 Elevation View of Locomotive and General Exhaust System

- If the flow rate obtained is between 5 and 12 ach, this is the system size.
- If the flow rate obtained is less than 5 ach, the designer could
  - Design for 5 ach.
  - Perform a more detailed analysis to verify that less than 5 ach will provide acceptable contaminant control. For rates less than the 0.0075 m^3/(s·m^2) recommended by ASHRAE *Standard* 62.1 or in the case of unusual sources, the presence of contaminants other than those from diesel exhaust in the space (e.g., liquid fuel) should also be considered.
- If the flow rate obtained is greater than 12 ach, the designer could
  - Adjust the other parameters to attempt to reduce the air change requirement.
  - Perform a more detailed analysis to verify the necessary air flow requirement.

Example 2. Perform design calculations for a passenger locomotive repair shop.

Step 1: Verify design parameters. The planned facility ceiling height is 9.1 m, which falls within the 6 to 13.7 m range for which the simplified equation is valid. The planned fan spacing is 15.2 m, which also falls within the required range of 6 to 18 m.

Step 2: Verify other facility characteristics.

- Exhaust fans: Exhaust openings with an area of approximately 2.3 m^2 will be used, and fans will be centered above each track.
- Locomotive: Operating locomotives are usually high idle or lower. When moving in, they will not exceed throttle position 1. Information obtained from the manufacturer of the locomotive most commonly serviced in this facility indicates an exhaust flow rate of 1.085 m^3/s, an exhaust temperature of 190°C, and NO_x generation of 3.475 kg/h. Radiator fans will not operate in the high idle position for this locomotive.
- Track-to-track spacing is 8.3 m. Locomotives may operate concurrently on adjacent tracks, but concurrent operation on the same track is not planned.
- These characteristics are reasonably similar to the assumptions upon which the simplified equation is based.

Step 3: Obtain emissions data and determine the design limit.

- The critical contaminant for this design is nitrogen dioxide (NO_2). Emission data from the manufacturer state that the NO_x generation rate is 3.475 kg/h. Field measurements conducted for ASHRAE research project RP-1191 (Musser and Tan 2004) showed that ambient NO_2 concentrations were about 13% of ambient NO_x levels. Therefore, the NO_2 generation rate is estimated to be 13% of the total, or 452 g/h. For an exhaust flow rate of 1.085 m^3/s, the concentration of NO_2 in the exhaust is 116 mg/m^3.

$$C_{emissions} = \left(\frac{452\ \text{g/h}}{1.085\ \text{m}^3/\text{s}}\right)\left(\frac{1}{3600\ \text{s/h}}\right)(1000\ \text{mg/g})$$
$$= 116\ \text{mg/m}^3$$

- OSHA currently requires a 5 ppm(v) ceiling for NO_2, but NIOSH and other sources recommend a 1 ppm(v) 15 min short-term exposure limit (STEL). The designer decides to select the lower 1 ppm(v) limit and to design for 0.5 ppm(v) (i.e., 0.94 mg/m^3) to allow for a safety factor for variations in emissions or operation.

$$\frac{0.5\ \text{ppm(v)} \times 46}{24.45} = 0.94\ \text{mg/m}^3$$

Step 4: Select a flow rate and solve for the contaminant concentration. Ceiling height is 9.1 m, and fan spacing is 15.2 m. Based on the placement of services in the shop, expect that the stack of an operating locomotive will be at most 3.8 m from the nearest exhaust fan, so $P = 0.5$. The shop does have a 1.2 m high platform where workers may stand, so Equation (20) is solved using a platform. First, try fans that provide 5 ach:

$$\begin{aligned} C_{occ} = {} & 10^{-3}(116\ \text{mg/m}^3)(22.5 - 0.773Q - 2.09P - 0.109X \\ & - 0.346Z + 0.0159QZ + 0.236PX + 0.0407PZ \\ & + 0.00190XZ - 0.00499PXZ) = 1.13\ \text{mg/m}^3 \end{aligned}$$

- Iterate between steps 5 and 4. With 5 ach, C_{occ} = 1.13 mg/m^3. This is greater than the desired limit of 0.94 mg/m^3. If the fan flow rate is increased to provide 10.5 ach, C_{occ} decreases to 0.94 mg/m^3. This meets the design criterion.

Step 5: Verify that the fan flow rate is between 5 and 12 ach. No further analysis is needed.

Exhaust Hood Design. A similar equation was also developed for design of exhaust hood systems. However, results from the parametric set of computational fluid dynamics simulations performed to develop the equation were shown to be highly specific to the situation and geometry shown in Figures 22 and 23. Therefore, these equations should not be used unless the given assumptions are exactly matched. For further information on hood design, see ACGIH (1998).

Step 1: Verify that the design parameters to be used in the simplified equation fall within the ranges for which it is valid.

- Hood mounting height H must be 0.9 to 2.4 m.
- Hood length L must be 1.5 to 3.4 m.
- Exhaust fan flow Q must provide 5 to 12 ach.

Step 2: Verify that other facility characteristics agree with the assumptions of the parametric study. These assumptions are as follows:

- Hood width W: 1.5 m.
- Hood placement: Hoods are centered above each track at 18.3 m intervals.
- Hood operation: All hoods switched on together.
- Ceiling height Z: 7.6 m.
- Locomotive exhaust temperature T: 177°C.
- Locomotive exhaust flow rate F: 0.944 m^3/s.
- Radiator fans: Radiator fans do not operate.
- Operating time: The results of the study are based on steady-state conditions, so it is not necessary to assume a maximum operating time.
- Concurrent operation: The study allows for concurrent operation on different tracks, but not for concurrent operation of more than one locomotive on the same track.
- Track-to-track spacing Y: 7.6 m.
- Ambient temperature: 32°C.

Step 3: Obtain emissions data for critical contaminants and determine the design indoor concentration limit for the critical contaminant. This can be done using the procedure described for general exhaust systems.

Step 4: Select a fan flow rate and calculate the maximum concentration to which occupants would be exposed using Equation (22).

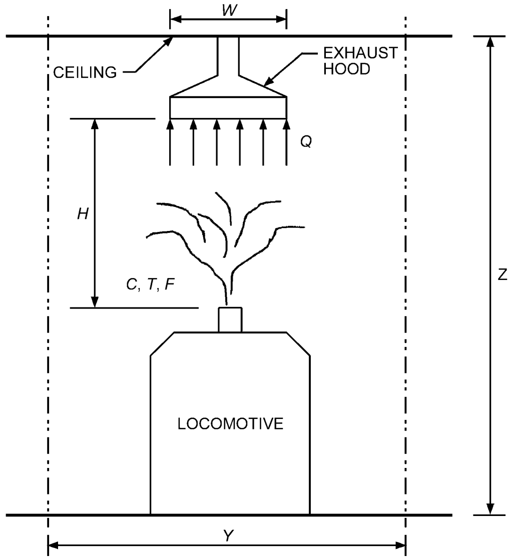


Fig. 22 Section View of Locomotive and Exhaust Hood System

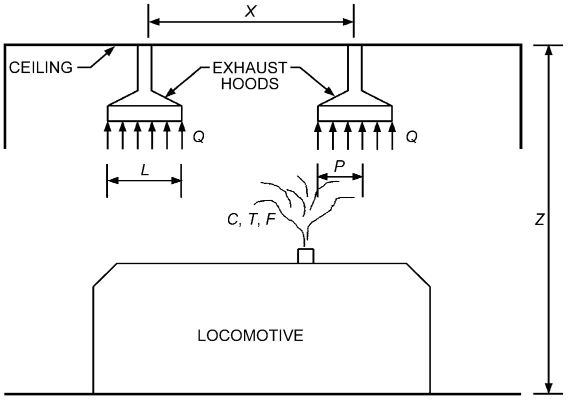


Fig. 23 Elevation View of Locomotive and Exhaust Hood System

Table 14 gives values for constants a to l for occupants standing on the floor or on a 1.2 m high platform.

$$\begin{aligned} C_{occ} = {} & 10^{-3} C_{emissions}(a + bQ + cP + dH + eL + fQP \\ & + gQH + hQL + iPH + jHL + kQPH + lQHL) \end{aligned} \tag{22}$$

where

C_{occ} = maximum time-averaged concentration of critical contaminant to which occupants could be exposed, mg/m^3
$C_{emissions}$ = concentration of critical contaminant in exhaust emissions, mg/m^3
a to l = constants in Table 14
Q = total exhaust fan flow rate required, ach; must be 5 to 12 ach
H = hood mounting height; must be 0.9 to 2.4 m
L = fan spacing; must be 1.5 to 3.4 m
P = locomotive offset position; dimensionless; P = 0 centered under hood and P = 1 under edge of hood. Other values for P can be calculated based on distance d of locomotive stack from center of nearest exhaust hood and hood length L:

$$P = \frac{2d}{L} \tag{23}$$

Table 14 Constants for Equation (22)

Constant	No Platform	With 1.2 m Platform
a	0.717	2.19
b	–0.160	–0.401
c	0.900	2.18
d	–0.168	–0.283
e	–0.0508	–0.275
f	–0.129	–0.332
g	0.0381	0.0684
h	0.0245	0.0846
i	–0.174	–0.351
j	0.0294	0.0575
k	0.0290	0.0560
l	–0.00588	–0.0134

Step 5: Compare C_{occ} obtained in step 4 with the concentration limit C_{limit} determined in step 3. If $C_{occ} < C_{limit}$, the selected flow rate is adequate. If $C_{occ} > C_{limit}$, repeat step 4 with a higher flow rate until a concentration less than the limit is obtained.

Step 6: Verify that the result is between 5 and 12 ach.

- If the flow rate obtained is between 5 and 12 ach, this is the system size.
- If the flow rate obtained is less than 5 ach, the designer could
  - Design for 5 ach.
  - Perform a more detailed analysis to verify that less than 5 ach will provide acceptable contaminant control. For rates less than the 0.0075 $m^3/(s \cdot m^2)$ recommended by ASHRAE *Standard* 62.1 or in the case of unusual sources, the presence of contaminants other than those from diesel exhaust in the space should also be considered (e.g., liquid fuel).
- If the flow rate obtained is greater than 12 ach, the designer could
  - Adjust other parameters to attempt to reduce the air change requirement.
  - Perform a more detailed analysis to verify the necessary air flow requirement.

8. EQUIPMENT

An enclosed vehicular facility's ability to function depends mostly on the effectiveness and reliability of its ventilation system, which must operate effectively under the most adverse environmental, climatic, and vehicle traffic conditions. A tunnel ventilation system should also have more than one dependable power source, to prevent interruption of service.

Fans

Fan manufacturers should be prequalified and should be responsible under one contract for furnishing and installing the fans, bearings, drives (including any variable-speed components), motors, vibration devices, sound attenuators, discharge/inlet dampers, actuators, and limit switches. Other ventilation-related equipment, such as ductwork, may be provided under a subcontract.

The prime concerns in selecting the type, size, and number of fans include the total theoretical ventilation airflow capacity required and a reasonable comfort margin. Fan selection is also influenced by how reserve ventilation capacity is provided either when a fan is inoperative, or during maintenance or repair of either the equipment or the power supply.

Selection (i.e., number and size) of fans needed to meet normal, emergency, and reserve ventilation capacity requirements of the system is based on the principle of parallel fan operation. Actual airflow capacities can be determined by plotting fan performance and system curves on the same pressure-volume diagram.

Fans selected for parallel operation may be required to operate in a particular region of their performance curves, so that airflow capacity is not transferred back and forth between fans. This is done by selecting a fan size and speed such that the duty-point total pressure, no matter how many fans are operating, falls below the minimum total pressure characterized by the bottom of the stall dip or unstable performance range. This may require consultation with the fan manufacturer, because this information is not typically available from published fan performance data. Fans operating in parallel should be of equal size and have identical performance curves. If airflow is regulated by speed control, all fans should operate at the same speed. If airflow is regulated by dampers or by inlet vane controls, all dampers or inlet vanes should be set at the same angle. For axial-flow fans, blades on all fans should be set at the same pitch or stagger angle.

Jet fans can be used for longitudinal ventilation to provide a positive means of smoke and air temperature management in tunnels. This concept was proven as part of the Memorial Tunnel Fire Ventilation Test Program (MHD/FHWA 1995). Although jet fans deliver relatively small air quantities at high velocity, the momentum produced is transferred to the entire tunnel, inducing airflow in the desired direction. Jet fans are normally rated in terms of thrust rather than airflow and pressure, and can be either unidirectional or reversible.

Number and Size of Fans. The number and size of fans should be selected by comparing several fan arrangements based on the feasibility, efficiency, and overall economy of the arrangement, and the duty required. Factors that should be studied include (1) annual power cost for operation, (2) annual capital cost of equipment (usually capitalized over an assumed equipment life of 30 years for mass transit tunnel fans, or 50 years for highway and railroad tunnel fans), and (3) annual capital cost of the structure required to house the equipment (usually capitalized over an arbitrary structure life of 50 years).

Two views are widely held regarding the proper number and size of fans: the first advocates a few high-capacity fans and the second prefers numerous low-capacity fans. In most cases, a compromise arrangement produces the greatest efficiency. The number and size of the fans should be selected to build sufficient flexibility into the system to meet the varying ventilation demands created by daily and seasonal traffic fluctuations and emergency conditions. Consideration should be given to satisfying emergency conditions during fan outages for maintenance or unplanned downtime.

In general, when selecting the number of fans, several issues may need to be considered, ranging from redundancy and space allocation, to design issues such as determining the number of control boxes, dampers, silencers, and similar equipment. In tunnel ventilation, the required fan airflow capacity is typically very large. If one fan is installed, the fan must be large, and this design provides zero redundancy in case of failure or maintenance. However, if many fans are installed, more space is required than for a single fan. Designs need to balance space allocation with an acceptable level of redundancy.

Jet fan sizing is usually limited by space available for installation in the tunnel. Typically mounted on the tunnel ceiling (above the vehicle traffic lanes) or on the tunnel walls (outside the vehicle traffic lanes), jet fans are sometimes placed in niches to minimize the height or width of the entire tunnel boundary. However, niches must be adequately sized to avoid reducing the thrust of the fans. A typical jet fan niche arrangement is provided in Figure 24.

For longitudinal ventilation using jet fans, the required number of fans is defined (once fan size and tunnel airflow requirements have been determined) by the total thrust required to overcome the tunnel resistance (pressure loss), divided by the individual jet fan thrust, which is a function of the mean air velocity in the tunnel. Jet fans installed longitudinally should be at least 7 to 10 tunnel hydraulic diameters apart so that the jet velocity does not affect the

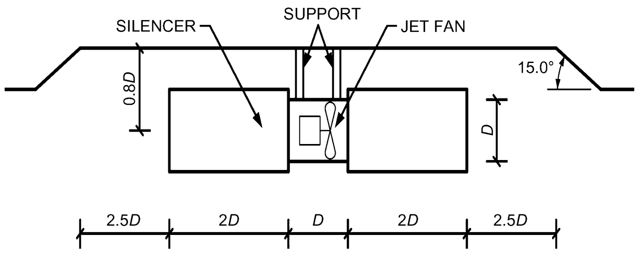


Fig. 24 Typical Jet Fan Arrangement in Niche

performance of downstream fans. Jet fans installed side by side should be at least two fan diameters (centerline to centerline) apart.

Type of Fan. Normally, ventilating an enclosed vehicular facility requires a large volume of air at relatively low pressure. Some fans have low efficiencies under these conditions, so the choice of a suitable fan type is often limited to a centrifugal, vaneaxial, or jet fan.

Special Considerations. Special attention must be given to a fan installed where **airflow and pressure transients** are caused by vehicle passage. If the transient tends to increase airflow through the fan (i.e., positive flow in front of the vehicle toward an exhaust fan, or negative flow behind the vehicle toward a supply fan), blade loading must not become high enough to produce long-term fatigue failures. If the disturbance tends to decrease airflow through the fan (i.e., negative flow behind the vehicle toward an exhaust fan or positive flow in front of the vehicle toward a supply fan), the fan performance characteristic must have adequate comfort margins to prevent an aerodynamic stall.

If the pressure pulses are large relative to the fan's total pressure capability, at either full or planned reduced-speed operation, it can result in an overblown condition. Motors, power, and mechanical systems should be designed for overblown operation if the motor needs to operate under these conditions.

The ability to **rapidly reverse** the rotation of a tunnel ventilation fan is important during an emergency. This requirement must be considered in selection and design of the fan and drive system.

Fan Design and Operation. Fans and fan components (e.g., blade-positioning mechanisms, drives, bearings, motors, controls, etc.) that must operate in the exhaust airstream during a fire or smoke emergency should be capable of operating at maximum speed under the temperatures specified by the following standards or calculation procedures:

- NFPA *Standard* 130 for mass transit and passenger rail tunnels
- NFPA *Standard* 502 for road tunnels
- Computer simulations or other calculations for the maximum expected temperatures, in railroad tunnels and other enclosed vehicular facilities

Fans and dampers that are operated infrequently or for emergency service only should be activated and tested at least once every month to ensure that all rotating elements are in good condition and properly lubricated. The period of activity should be long enough to achieve stabilized temperatures in fan bearings and motor windings.

Inlet boxes can be used to protect centrifugal fan bearings and drives from high temperatures, corrosive gases, and particulate matter in exhaust air during emergency operating mode. This arrangement requires special attention to fan shaft design because of overhung drive loads (see the section on Fan Shafts).

Reversible axial flow fans should be able to be rapidly reversed from the maximum design speed in one direction to the maximum design speed in the opposite direction in less than 60 s. Fan design should include the effects of temperature changes associated with reversing airflow direction. All components of reversible fans should be designed for a minimum of 5000 cycles without damage.

Housings for variable-pitch axial flow fans should be furnished with instruments to measure airflow in both directions. Capped connections should be provided for measuring the pressure developed across the fan. The fan should also be protected from operating in a stall region.

To minimize blade failure in axial flow fans, the following precautions should be taken:

- Blades should be secured to the hub by positive locking devices.
- The fan inlet (and discharge, if reversible) should be protected against entry of foreign objects that could damage the rotating assembly.
- The natural frequency (static and rotating) of the blade and the maximum stress on the blade surface (for all operating points on the fan characteristic curve) should be measured during factory testing.
- For mass transit and rail systems, fans subjected to airflow and air pressure reversals caused by train passage should be designed (and tested, for verification) to withstand 4 000 000 cycles of airflow reversals.

When a fan includes a variable-frequency drive (VFD), factory testing with a production version of the VFD should be done to ensure adequate operation and compatibility with the fan system. Fans that are run by VFDs should have an installed static blade with a first bending natural frequency at least four times higher than the maximum intended running speed (e.g., an 1180 rpm fan's first bending frequency should be at least 79 Hz). If installed blades have a first bending frequency below this value, the VFD should be programmed to avoid speeds that are potentially problematic.

Jet fan blades should be strong enough to withstand the air temperatures created by a fire. Design calculations for jet fans should consider that the fire might destroy the fan(s) at the fire location, and that the jet fans downstream of the fire will operate under high temperatures and reduced thrust.

Fan Shafts. Fan shafts should be designed so that the maximum deflection of assembled fan components, including forces associated with the fan drive, does not exceed 0.42 mm per metre of shaft length between centers of the bearings. For centrifugal fans where the shaft overhangs the bearing, the maximum deflection at the centerline of the fan drive pulley should not exceed 0.42 mm per metre of shaft length between the center of the bearing and the center of the fan drive pulley.

Good practice suggests that the fundamental bending mode frequency of the assembled shaft, wheel, or rotor be more than 50% higher than the highest fan speed. The first resonant speed of all rotational components should be at least 125% above the maximum speed. The fan assembly should be designed to withstand, for at least 3 min, all stresses and loads from an overspeed test at 110% of maximum design fan speed.

Bearings. Fan and motor bearings should have a minimum equivalent L10 rated life of 10 000 h, as defined by the American Bearing Manufacturers Association (ANSI/ABMA 2000). Special attention must be given to belt-driven fans, because improper tensioning or overtensioning of belts can drastically reduce the bearing life, belt life, and possibly shaft life.

For **axial-flow fans** and **jet fans**, each fan motor bearing and fan bearing should have a monitoring system that senses individual bearing vibrations and temperatures, and provides a warning alarm if either rises above the manufacturer-specified range. Jet fan motors should have an industrial protection class (IP rating) of 55 or higher, which has bearings with washdown-rated seals.

Because of their low speed (generally less than 450 rpm), **centrifugal fans** are not always provided with bearing vibration sensors, but they do require temperature sensors with warning alarm and automatic fan shutdown. Bearing pedestals for centrifugal fans should provide rigid support for the bearings with negligible impediments to airflow. Static and dynamic loading of the shaft and the impeller, and the maximum force from tension in the belts, should be considered.

Corrosion-Resistant Materials. Choosing a particular material or coating to protect a ventilation fan from corrosive gas is a matter of economics. Selection of the material and/or coating should be based on the installation environment, fan duty, and an expected service life of 50 years.

Sound. For ventilation fan sound attenuator design, construction documents should specify the following:

- Speed and direction of airflow, and number of operating fans
- Maximum dBA rating or NC curve(s) acceptable under installed conditions, and locations of fan supply inlet and exhaust outlet where these requirements apply
- OSHA or local requirements for jet-fan-generated noise limits, which may require silencers of 1 to 2 fan diameters in length
- The dBA rating required at certain specific locations, such as intake louvers, discharge louvers, or discharge stacks, may not exceed OSHA or local requirements
- That the fan manufacturer must furnish and install the acoustical treatment needed to bring the sound level down to an acceptable value if measured sound values exceed the specified maximum values at the defined boundaries of the fan manufacturer's scope of supply
- NFPA-recommended maximum noise levels for emergency fan operations

Dampers

Dampers play a major role in overall tunnel safety and the successful operation of a tunnel ventilation system. Dampers regulate airflow into and out of the tunnel, through either natural or forced ventilation, to maintain acceptable temperatures. Dampers also relieve pressure: opening and closing dampers allows tunnel air to be driven out of ventilation shafts located in front of moving vehicles, and for fresh air to be drawn into tunnels by ventilation shafts located behind moving vehicles. Dampers are also used with fans to dilute or remove carbon monoxide (CO), flammable gases, or other toxic fumes from tunnels. However, the most important function of dampers is to direct ventilation air and smoke flow during a fire emergency. In this function, fans and dampers operate in conjunction to exhaust smoke and control its flow in the tunnel in support of passenger evacuations and firefighter ingress.

Damper Design. Tunnel ventilation damper design requires a thorough understanding of design criteria, installation methods, environmental surroundings, equipment life expectancy, maintenance requirements, and operating system. Damper construction varies, but the general construction is based on the following design criteria:

- Maximum fan operating pressure
- Normal and rogue tunnel air pressures
- Maximum air temperature
- Maximum air velocity
- Corrosion protection
- Maintainability and life expectancy of equipment
- Maximum damper module size
- Maximum air leakage

Fan Pressure. The maximum operating pressure that the damper will withstand during normal or emergency ventilation operations is typically the maximum pressure that the fan can generate at shutoff. This air pressure is generally 1.0 to 12.5 kPa.

Normal and Rogue Tunnel Pressures. Some dampers in the track area of a train tunnel see much higher positive- and negative-pressure pulses than the maximum pressure generated by the fan. These high-pressure pulses are caused by the piston action of trains moving through the tunnel. A closed damper is subjected to positive pressures as trains approach, and to negative pressures as trains pass. This pressure reversal subjects damper blades and related components to reverse bending loads that must be considered to prevent premature fatigue failures. The magnitude of the pulsating pressure depends on factors such as maximum train speed, unidirectional or bidirectional traffic, tunnel length, blockage ratio, clearance between train and tunnel walls, and amount of air pushed through the dampers.

Pulsating pressure is part of normal tunnel operation. However, a rogue train condition (e.g., a train operating at high speed during an emergency or a runaway train) could occur once or twice during the lifetime of a tunnel ventilation system. Dampers must be designed for both day-to-day fatigue and for maximum train-speed conditions.

Design specifications should require that the damper and its components meet reverse bending load criteria for from 1 to 6 million reverse bending cycles for normal, day-to-day train operations. This number equates to a train passing a damper once every 5 to 20 min for 30 to 50 years. The number of cycles can be adjusted for each application. In addition, the specifying engineer should indicate the pressure that could result from a (once or twice in a lifetime) rogue train condition.

Typically, actuators for tunnel dampers must be selected to operate against the maximum fan pressure. Because reversing pressures only occur briefly, and because normal train operations cease during an emergency, actuators are not expected to operate under either reverse pressure or rogue train conditions.

Temperature. The maximum temperature can vary for each tunnel project; some specifying engineers use the temperature limits recommended by NFPA. Typical equipment specifications state that dampers, actuators, and accessories should meet the operational requirements of the emergency ventilation fan system described in NFPA *Standard* 130: "Emergency ventilation fans, their motors, and all related components exposed to the exhaust airflow shall be designed to operate in an ambient atmosphere of 250°C for a minimum of 1 h with actual values to be determined by design analysis. In no case shall the operating temperatures be less than 150°C."

Some tunnel design engineers have specified higher air temperature criteria based on additional design considerations. A few road tunnels have been designed for the possibility of two tanker trucks carrying flammable liquids exploding from an accident in the tunnel, which would subject tunnel dampers to very high temperatures. Dampers for projects of this type, or others projects with special considerations, have been designed for maximum temperatures up to 425°C. The specifying engineer must evaluate design conditions for each project and determine what the maximum temperature could be.

Dampers, and especially damper actuators, must be specially constructed to operate reliably in high-temperature conditions for extended periods. It is important to verify that the proposed equipment can provide this required safety function. Because standard testing procedures have not been developed, a custom high-temperature test of a sample damper and actuator should be considered for inclusion in the equipment specifications.

Air Velocity. The maximum air velocity for a tunnel damper design is determined from the maximum airflow expected through the damper during any operating condition. Maximum airflow could be generated from more than one fan, depending on the system design. Actuators for tunnel dampers are typically selected to operate against the maximum airflow that dampers will be exposed to in a worst-case scenario. Thus, the maximum airflow must be specified. It is important that the engineer understands the effect of damper free area on expected airflow and pressure loss. Air velocity through a damper can vary significantly depending on damper construction and the installation configuration used.

A multiple-panel damper assembly usually has less free area than a single panel damper because of the additional blockage caused by its vertical and/or horizontal mullions. A multiple-panel damper assembly with 60 to 70% free area can have two to four times the pressure loss of a single-panel damper with 80% free area. Therefore, airflow through the multiple-panel damper assembly can be significantly lower than that through a comparable single-panel damper.

The configuration of the damper installation can also affect free area, airflow, and pressure loss. For example, a damper can either be mounted to the face of an opening or in the opening itself. The damper mounted in the opening has a smaller free area because of the additional blockage of the damper frame, resulting in lower airflow and higher pressure loss. Damper performance also depends on where the damper is mounted (e.g., in a chamber, at one or the other end of a duct). AMCA *Standard* 500-D has more information on damper mounting configurations.

Corrosion Protection. Construction materials for tunnel projects vary considerably; their selection is usually determined based on one or more of the following reasons:

- Initial project cost
- Environmental conditions
- Life expectancy of the equipment
- Success or failure of previous materials used on similar projects
- Engineer's knowledge of and/or experience with the materials required to provide corrosion protection
- Design criteria (e.g., tunnel air pressure, temperature, velocity)

The corrosion resistance of a damper should be determined by the environment in which it will operate. A damper installation near a saltwater or heavy industrial area may need superior corrosion protection compared to one in a rural, nonindustrialized city. Underground or indoor dampers may need less corrosion protection. However, many underground dampers are also exposed to rain, snow, and sleet. These and other factors must be evaluated by the engineer before a proper specification can be written.

Tunnel dampers have been made from commercial-quality galvanized steel, hot-dipped galvanized steel, anodized aluminum, aluminum with a duranodic finish, carbon steel with various finishes, and stainless steel, including types 304, 304L, 316, 316L, and 317.

Maintainability and Life Expectancy of Equipment. These issues are of great concern when specifying dampers that may be difficult to access regularly for servicing, inspection, or maintenance. In addition, the equipment may be difficult to replace if it fails prematurely because it was marginally designed for the pressures, temperatures, corrosion resistance, etc., required for the application.

Thus, some specifying engineers purposely design dampers with a more robust construction. Dampers may be specified with heavier and/or more corrosion-resistant materials than may be required for the application, in hopes of reducing operational problems and maintenance costs and extending the life expectancy of the product. Typical methods used to design dampers of more robust construction include the following:

- Limiting blade, frame, and linkage deflections to a maximum of $L/360$
- Selecting actuators for 200 to 300% of the actual damper torque required
- Using large safety factors for stresses and deflections of high stress components
- Specifying heavier material sizes and gages than necessary
- Using more corrosion-resistant materials and finishes than required
- Using slower damper activation times (from full-close to full-open and vice versa)

Many damper specifications include a quality assurance (QA) or system assurance program (SAP) to ensure that required performance levels are met. Others include an experience criterion that requires damper manufacturers to have five installations with five or more years of operating experience; a list of projects and contact names must be submitted so the current customer can communicate with past customers regarding the product performance. These requirements help ensure that reliable products are supplied.

Module Size. The maximum damper module size is one of the most important initial-cost factors. Many dampers can be made as a single-module assembly or in several sections that can be field assembled into a single-module damper. However, some damper openings are very large and it may not be practical to manufacture the damper in a one-piece frame construction because of shipping, handling, and/or installation problems.

Generally, initial cost is lower with fewer modules because they have fewer blades, frames, jackshafts, actuators, and mullion supports. However, other factors, such as job site access, lifting capabilities, and installation labor costs, must also be included in the initial-cost analysis. These factors vary for each project, so the specifying engineer must evaluate each application separately.

Air Leakage. The specifying engineer must consider air leakage through the damper when evaluating a design. Leakage is usually specified in terms of cubic metres per second per square metre of damper face area, at a specific air pressure. As differential air pressure increases across the damper, so does air leakage. Leakage is, therefore, a function of air pressure and damper crack area, rather than of airflow. To reduce leakage, the number or size of leakage paths must be reduced. The most common method is adding damper blades and/or jamb seals, which can reduce leakage to an acceptable value.

Some specifications note the allowable damper air leakage as a percentage of the normal or maximum airflow. However, it is important to recognize that this is only an acceptable practice if the airflow and associated pressure are known.

Damper Applications and Types. Dampers allow or restrict airflow into a tunnel, and balance airflow in a tunnel. **Fan isolation dampers** can be installed in multiple-fan systems to (1) isolate any parallel, nonoperating fan from those operating, to prevent short-circuiting and airflow/pressure losses through the inoperative fan; (2) prevent serious windmilling of an inoperative fan; and (3) provide a safe environment for maintenance and repair work on each fan. Single-fan installations may also have a fan isolation damper to prevent serious windmilling from natural or piston-effect drafts and facilitate fan maintenance.

Ventilation dampers control the amount of fresh air supplied to and exhausted from the tunnel and station areas. They may also serve as **smoke exhaust dampers** (SEDs), **bypass dampers** (BDs), **volume dampers** (VDs), and **fire dampers** (FDs), depending on their location and design. Two types of ventilation dampers are generally used: (1) trapdoor, which is installed in a vertical duct, such that the door lies horizontal when closed; and, (2) multiblade louver with parallel-operating blades. Both types can be driven by either an electric or pneumatic actuator; the fan controller operates the damper actuator. During normal operation, the damper usually closes when the fan is shut off and opens when the fan is turned on.

The trapdoor damper is simple and works satisfactorily where a vertical duct enters a plenum fan room through an opening in the floor. This damper is usually constructed of steel plate, with welded angle iron reinforcements; it is hinged on one side and closed by gravity against the embedded angle frame of the opening. The opening mechanism is usually a shaft sprocket-and-chain device. The drive motor and gear drive mechanism, or actuator, must develop sufficient force to open the damper door against the maximum (static) air pressure differential that the fan can develop. This pressure can be obtained from the fan performance curves. Limit switches start and stop the gear-motor drive or actuator at the proper position.

Fan isolation and ventilation dampers in places other than vertical ducts should have multiblade louvers. These dampers usually consist of a rugged channel frame, the flanges of which are bolted to the flanges of the fan, duct, wall, or floor opening. Damper blades are assembled with shafts that turn the bearings mounted on the outside of the channel frame. This arrangement requires access outside the duct for bearing and shaft lubrication, maintenance, and linkage operation space. Multiblade dampers should have blade edge and/or end seals to meet air leakage requirements for the application.

The trapdoor damper, properly fabricated, is inherently a low-leakage design because of its weight and the overlap at its edges. Multiblade dampers can also have low air leakage, but they must be carefully constructed to ensure tightness on closing. The pressure drop across a fully opened damper and the air leakage rate across a fully closed damper should be verified by the appropriate test procedure in AMCA *Standard* 500-D. A damper that leaks excessively under pressure can cause the fan to rotate counter to its power rotation, thus making restarting dangerous and possibly damaging to the fan motor drive.

Actuators and Accessory Selections. Tunnel damper specifications typically call for dampers, actuators, and accessories to meet the operational requirements of **emergency ventilation fans**, as described by NFPA *Standard* 130. Damper actuators are normally specified to be electric or pneumatic. Actuator selection is determined by the engineer or the customer and is usually decided by available power or initial and/or long-term operating cost.

Pneumatic Actuators. Pneumatic actuators are available in many sizes and designs; rack and pinion, air cylinder, and Scotch yoke are common configurations. Each can be of either double-action (i.e., air is supplied to operate the damper in both directions) or spring-return construction. A spring-return design uses air to power it in one direction and a spring to drive it in the opposite direction; it is selected when it is desirable to have the damper fail to a set position on loss of air supply. Many manufacturers make pneumatic actuators; several manufacturers make both double-acting and spring-return designs capable of operating at 250°C for 1 h.

Electric Actuators. Electric actuators are also available in a variety of designs and sizes. They can be powered in both directions to open and close the damper; in this case the actuator usually fails in its last position on loss of power. Electric actuators that are powered in one direction and spring-driven in the opposite direction are also available. As with pneumatic actuators, spring return is selected when it is desirable to have the damper fail to a particular position on loss of power. There are fewer manufacturers of electric actuators than pneumatic actuators, and most do not make a spring-return design, especially in larger-torque models. Also, very few electric actuators are capable of operating at 250°C for 1 h, particularly for spring-return designs.

Actuator Selection. Actuators for tunnel dampers are typically sized to operate against the maximum airflow or velocity and pressure that will occur in a worst-case scenario. The maximum air velocity corresponds to the maximum airflow expected through the damper during any of its operating conditions. In addition, the maximum airflow could come from more than one fan, depending on system design. The maximum pressure on the damper during normal or emergency ventilation is typically the maximum pressure that the fan can generate at shutoff.

Actuators are sized and selected to (1) overcome the frictional resistance of blade bearings, linkage pivots, jackshafting assemblies, etc.; and (2) compress the blade and jamb seals to meet specified air leakage requirements. Therefore, the specifying engineer must determine maximum airflow (or air velocity) and pressure conditions, and maximum air leakage criteria.

Other factors in actuator selection are reliability and maintenance requirements. Although pneumatic actuators are considered more reliable than electric ones, the larger number of components in a pneumatic system and the cumulative risk of failure of any one component make the overall reliability of both systems similar.

Safety factors in actuator selection are not always addressed in tunnel damper specifications. This omission can result in operational problems if a manufacturer selects actuators too close to the required operating torque. Tunnel dampers are expected to function for many years when properly maintained. Also, damper manufacturers determine their torque requirements based on square, plumb, and true installations. These factors, plus the fact that dirt and debris build-up can increase damper torque, suggest that a minimum safety factor of at least 50% should be specified. Greater safety factors can be specified for some applications; however, larger actuators require larger drive shafts with higher initial cost.

Supply Air Intake. Supply air intakes require careful design to ensure that air drawn into the ventilation system is of the best quality available. Factors such as recirculation of exhaust air or intake of contaminants from nearby sources should be considered. Louvers or grilles are usually installed over air intakes for aesthetic, security, or safety reasons. Bird screens are also necessary if the openings between louver blades or grilles are large enough to allow birds to enter.

Because of the large volumes of air required in some ventilation systems, it may not be possible for intake louvers to have face air velocities low enough to be weatherproof. Therefore, intake plenums, ventilation shafts, fan rooms, and fan housings often need water drains. Windblown snow can also enter the fan room or plenum, but snow accumulation usually does not prevent the ventilation system from operating satisfactorily, if additional floor drains are located near the louvers.

Sound attenuation devices may be needed in fresh air intakes or exhaust outlets to keep fan-generated noise from disturbing the outdoor environment. If noise reduction is required, the total system (i.e., fans, housings, plenums, ventilation building, and location and size of air intakes and exhaust outlets), should be investigated. Fan selection should be based on the total system, including pressure drop from sound attenuation devices.

Exhaust Outlets. Exhaust air from ventilation systems should be discharged above street level and away from areas with human occupancy. Contaminant concentrations in exhaust air should not be a concern if the system is working effectively. However, odors and entrained particulate matter in exhaust make discharge into occupied areas undesirable. Exhaust stack discharge velocity, usually a minimum of 10 m/s, should be high enough to disperse contaminants into the atmosphere.

Evasé (flared) outlets have been used to regain some static pressure and thereby reduce exhaust fan energy consumption. Unless the fan discharge velocity is over 10 m/s, the energy savings may not offset the cost of the evasé outlets.

In a vertical or near-vertical exhaust fan discharge connection to an exhaust duct or shaft, rainwater runs down the inside of the stack into the fan. This water dissolves material deposited from vehicle exhaust on the inner surface of the stack and becomes extremely corrosive. Therefore, fan housings should be corrosion-resistant or specially coated to protect the metal.

Discharge louvers and gratings should be sized and located so that their discharge is not objectionable to pedestrians or contaminating to nearby air intakes. Airflow resistance across the louver or grating should also be minimized. Discharge air velocities through sidewalk gratings are usually limited to 2.5 m/s. Bird screens should be provided if the exhaust airstream is not continuous (i.e., 24 h/day, 7 days/week), and the openings between louver blades are large enough to allow birds to enter.

Corrosion resistance of the louver or grating should be determined by the corrosiveness of the exhaust air and the installation environment. Pressure drop across the louvers should be verified by the design engineer using the appropriate test procedure in AMCA *Standard* 500-L.

9. NATIONAL AND INTERNATIONAL SAFETY STANDARDS AND GUIDELINES

National Fire Protection Association (NFPA)

NFPA developed fire protection standards for both road tunnels and for rapid transit facilities. The standard for transit systems is known as NFPA *Standard* 130, and the standard for road tunnels, bridges, and other limited-access roads is NFPA *Standard* 502.

In addition to *Standards* 130 and 502, NFPA publishes many standards and codes that are applicable to enclosed vehicular facilities, including the following:

- Standard for Portable Fire Extinguishers, NFPA 10, 2010
- Standard for the Installation of Sprinkler Systems, NFPA 13, 2010
- Standard for the Installation of Standpipe and Hose Systems, NFPA 14, 2010
- Standard for the Installation of Stationary Pumps for Fire Protection, NFPA 20, 2010
- Standard for Water Tanks for Private Fire Protection, NFPA 22, 2008
- Flammable and Combustible Liquids Code, NFPA 30, 2008
- Code for Motor Fuel Dispensing Facilities and Repair Garages, NFPA 30A, 2008
- Standard for Spray Application using Flammable or Combustible Materials, NFPA 33, 2011
- Vehicular Gaseous Fuel Systems Code, NFPA 52, 2010
- Liquefied Natural Gas (LNG) Vehicular Fuel Systems Code, NFPA 57, 2002
- Liquefied Petroleum Gas Code, NFPA 58, 2011
- National Electrical Code®, NFPA 70, 2011
- Recommended Practice for Electrical Equipment Maintenance, NFPA 70B, 2010
- National Fire Alarm and Signaling Code®, NFPA 72®, 2010
- Standard for Fire Doors and Other Opening Protectives, NFPA 80, 2010
- Standard for Parking Structures, NFPA 88A, 2011
- Standard for Repair Garages, NFPA 88B, 1997
- Life Safety Code®, NFPA 101®, 2009
- Standard for Emergency and Standby Power Systems, NFPA 110, 2010
- Standard on Stored Electrical Energy Emergency and Standby Power Systems, NFPA 111, 2010
- Standard for Safeguarding Construction, Alteration, and Demolition Operations, NFPA 241, 2009
- Standard on Emergency Services Incident Management System, NFPA 1561, 2008
- Standard for Fire Hose Connections, NFPA 1963, 2009

World Road Association (PIARC)

PIARC, or the World Road Association (formerly the Permanent International Association of Road Congresses), has for many years published technical reports on tunnels and tunnel ventilation in conjunction with their quadrennial World Road Congresses. The PIARC Technical Committee on Road Tunnel Operation (C3.3) and its working groups published several important specific documents on tunnel ventilation and fire safety:

- Classification of Tunnels, Existing Guidelines and Experiences, Recommendations, 05.03.B, 1995
- Road Tunnels: Emissions, Environment, Ventilation, 05.02.B, 1996
- Fire and Smoke Control in Road Tunnels, 05.05.B, 1999
- Pollution by Nitrogen Dioxide in Road Tunnels, 05.09.B, 2000
- Cross Section Geometry in Uni-Directional Tunnels, 05.11.B, 2002
- Cross Section Design of Bidirectional Road Tunnels, 05.12.B, 2004
- Good Practice for the Operation and Maintenance of Road Tunnels, 05.13.B, 2004
- Road Tunnels: Vehicle Emissions and Air Demand for Ventilation, 05.14.B, 2004
- Traffic Incident Management Systems Used in Road Tunnels, 05.15.B, 2004
- Systems and Equipment for Fire and Smoke Control in Road Tunnels, 05.16.B, 2007
- Integrated Approach to Road Tunnel Safety, 2007R07, 2007
- Risk Analysis for Road Tunnels, 2008R02, 2008
- Management of the Operator—Emergency Teams Interface in Road Tunnels, 2008R03, 2008
- Road Tunnels: A Guide to Optimising the Air Quality Impact upon the Environment, 2008R04, 2008
- Road Tunnels: An Assessment of Fixed Fire Fighting Systems, 2008R07, 2008
- Tools for Road Tunnel Safety Management, 2009R08, 2009

Country-Specific Standards and Guidelines

Many countries publish tunnel guidelines and standards primarily for use in their country; however, many of these documents do provide an insight into numerous unique tunnel applications. A partial list of those available is as follows:

- Design Guidelines Tunnel Ventilation, RVS 9.261 & RVS 9.262, Transportation and Road Research Association, National Roads Administration, Austria, 1997
- Regulations on Technical Standards and Conditions for Design and Construction of Tunnels on Roads, Croatia, 1991
- Design of Road Tunnels, *Standard* CSN 73 7507, Czech Republic
- Road Tunnel Equipment, *Guideline* TP 98, Czech Republic
- Inter-Ministerial *Circular* 2000-63: Safety in the Tunnels of the National Highways Network, Ministry of the Establishment, Transport and Housing, France, 2000
- Guidelines for Equipment and Operation of Road Tunnels, Road and Transportation Research Association (RABT), Federal Ministry of Traffic, Germany, 2006
- Safety of Traffic in Road Tunnels with Particular Reference to Vehicles Transporting Dangerous Materials, Italy, 1999
- National Safety Standard of Emergency Facilities in Road Tunnels, Japan Road Association, Japan, 2001
- Recommendations for the Ventilation of Road Tunnels Public Works and Water Management (RWS), the Netherlands, 2005
- *Norwegian Design Guide—Road Tunnels*, Public Roads Administration, Directorate of Public Roads, Norway, 1992
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Building and Fire Codes

Often, building and fire codes have supplementary information and requirements applicable to a specific type of facility. For example, ventilation of a vehicle parking garage is also governed by the applicable building code. Some of the commonly used codes are as follows:

- The **International Building Code® (IBC®)** with its own subset of mechanical codes such as the *International Plumbing Code®* (IPC®) and the *International Mechanical Code®* (IMC®), as well as the *International Existing Buildings Code®*, *International Fire Code®*, and *International Fuel Gas Code®*.
- **National building codes** were the Uniform Building Code (UBC), Building Officials Code Association (BOCA), and the Southern Building Code Conference (SBCC), each of which was applicable in different parts of the country but now have been replaced by the IBC.
- Most states have their own **state building and fire codes** with specific modifications to the IBC or other as applicable for the conditions specific to the state, such as seismic requirements.
- Many cities and municipalities have their own **local building and fire codes**. The designer should be aware of the local code governing the facility. Many cities have adopted specific NFPA standards into their codes and some amend these standards. The facility's design is required to conform to the requirements of the amended standard, unless a specific waiver is applied for and obtained.

Ancillary areas of tunnels such as electrical and mechanical equipment rooms, which are often adjacent to the tunnel they serve, are governed by the applicable building codes. For separation requirements between these ancillary spaces and the tunnel, the more stringent of the requirements between the building code and the applicable NFPA standard applies. The authority having jurisdiction should always be consulted when there is any doubt in the application of this separation requirement.

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