CHAPTER 13

ENCLOSED VEHICULAR FACILITIES

THIS chapter covers ventilation requirements for normal climate control, contaminant level control, and emergency smoke/temperature management in road tunnels, rail tunnels, and subway stations, as well as in diesel locomotive facilities, enclosed parking structures, bus garages, bus terminals, and tollbooths. Also covered are design approaches for various natural and mechanical ventilation systems, as well as applicable ventilation equipment.

ROAD TUNNELS

A road tunnel is an enclosed 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 airright structures over a roadway or overbuilds of a roadway.

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 terms of 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

Three types of mechanical ventilation are typically considered for road tunnels: normal, emergency, and temporary.

Normal ventilation is used during ordinary traffic operations to maintain acceptable levels of contaminants in the tunnel. It addresses both free-flowing traffic (vehicle speeds greater than 30 mph) and congested traffic [vehicles moving at maximum speeds less than 30 mph or, more likely, at vehicle speeds of 0 (idling) to 10 mph].

Emergency ventilation is required during a fire emergency to control and remove smoke and hot gases. Its primary objective is to provide an evacuation path that is sufficiently clear of smoke and hot gases, and is maintained at a sufficiently low temperature to permit safe evacuation of motorists. Emergency ventilation is also intended to provide safe access for firefighters and to protect the tunnel structure against heat-related failures.

Temporary ventilation is needed during original construction or while work is being done in a finished tunnel. It is usually removed after construction is complete. 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).

VENTILATION SYSTEMS

Ventilation must dilute contaminants during normal 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 1200 and 2200 ft.

Natural Ventilation

Naturally ventilated tunnels rely primarily on atmospheric conditions to maintain airflow and a satisfactory environment in the tunnel. The piston effect of moving traffic provides additional airflow. The chief factor affecting the tunnel environment is the pressure differential created by differences in elevation, the ambient air temperature, or wind between the two tunnel portals. Unfortunately, none of these factors reliably provide continuous, consistent results. A change in wind direction or speed can negate other natural effects, including the piston effect. To achieve natural ventilation, the pressure differential must be large enough to overcome tunnel resistance, which is influenced by tunnel length, cross section, and wall roughness, as well as the number of vehicles in the tunnel and the local air density.

Airflow through a naturally ventilated tunnel can be portal-to-portal (Figure 1A) or portal-to-shaft (Figure 1B). 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 1A.

Introducing bidirectional traffic into such a tunnel will further reduce longitudinal airflow and increase 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 naturally ventilated tunnel with an intermediate shaft (Figure 1B) 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 1000 ft 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 800 and 1000 ft 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

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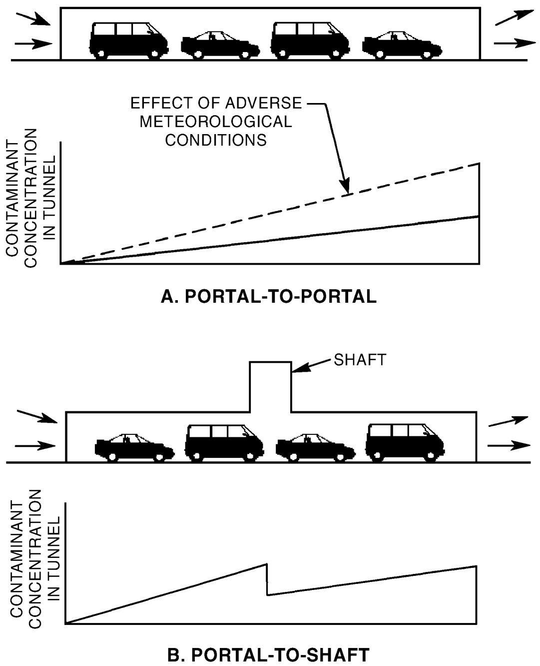

Fig. 1 Natural Ventilation

Table 1 Smoke Movement During Natural Ventilation Tests
(Memorial Tunnel Fire Ventilation Test Program)

Test No.	Fire Heat Release Rate, 10^6 Btu/h Nominal	Fire Heat Release Rate, 10^6 Btu/h Peak	Smoke Layer Begins Descent, min	Smoke Fills Tunnel Roadway, min	Peak Smoke Velocity, fpm
501	68	99	3+	5	1200
502	170	194	1+	3	1600

Note: Tunnel grade is 3.2%.

tunnels over 800 ft 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 will tend to flow upgrade. The steeper the grade, the faster the smoke will move, 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 1, 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. Among the alternatives available for road tunnels are longitudinal ventilation, semitransverse ventilation, and full transverse ventilation.

Longitudinal Ventilation. This type of 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 injection, jet fan operation, or a combination of injection and extraction at intermediate points in the tunnel.

Injection longitudinal ventilation, frequently used in rail tunnels, uses centrally located fans to inject air into the tunnel through a high-velocity Saccardo nozzle, as shown in Figure 2A. 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 an extremely 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 discharge velocity and the angle of the nozzle. This type of ventilation is most effective with unidirectional traffic flow.

With injection longitudinal ventilation, the 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 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 advantages of using a Saccardo nozzle-based longitudinal ventilation system over a jet fan-based system include the following:

- Reduced tunnel height
- Reduced number of moving parts to maintain
- Performing maintenance without impeding traffic flow
- Lower tunnel noise levels
- Higher fan efficiency
- Less chance of equipment being directly exposed to fire or hot gases

A longitudinal ventilation system with one fan shaft (Figure 2B) 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 2C). 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 exhaust shaft to supply 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 2D). 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 outside 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

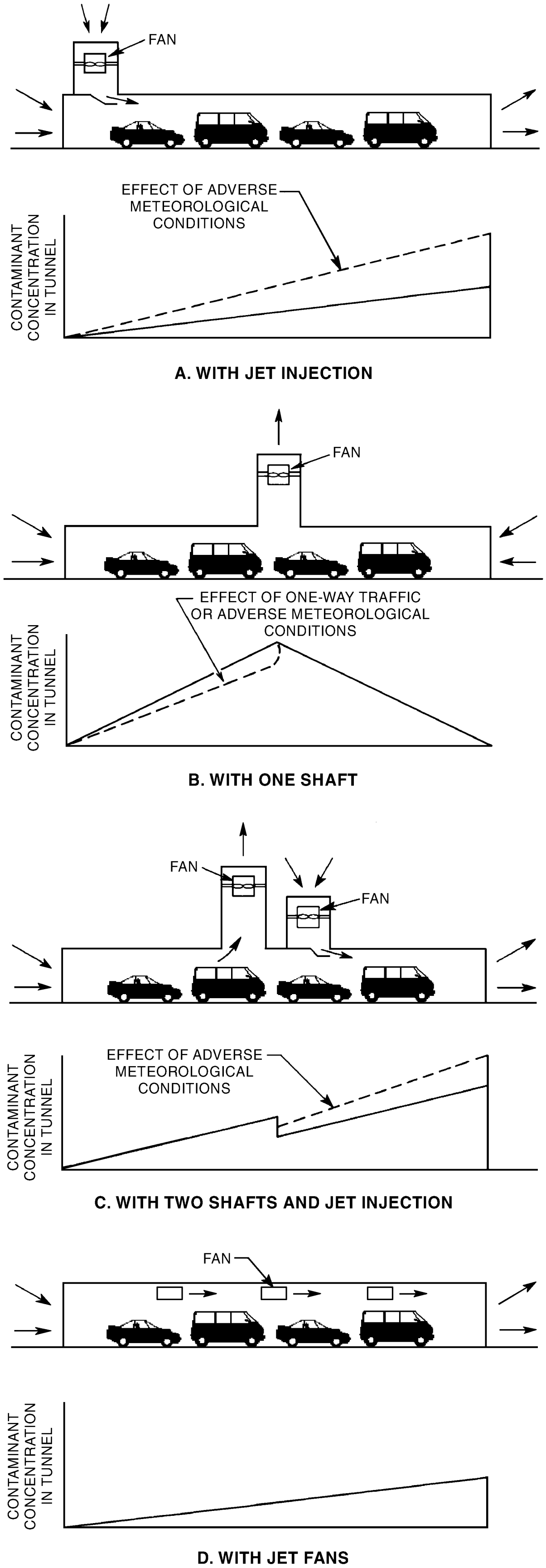

Fig. 2 Longitudinal Ventilation

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. Semitransverse ventilation can be configured for supply or exhaust. This type of ventilation involves the uniform distribution (supply) and/or collection (exhaust) of air throughout the length of a road tunnel. Semitransverse ventilation is normally used in tunnels up to about 7000 ft; 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 the movement of the vehicles, thus reducing the contaminant level in the first half of the tunnel (Figure 3A).

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 respirable 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 3B) in a tunnel with unidirectional traffic flow produces a maximum contaminant concentration at the exit portal. In a tunnel with bidirectional traffic flow, the maximum concentration of contaminants is located near the center of the tunnel. A combination supply and exhaust semitransverse system (Figure 3C) should be applied only in a unidirectional tunnel where the air entering with the traffic stream is exhausted in the first half of the tunnel, and the 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. Full transverse ventilation is used in extremely long tunnels and in tunnels with heavy traffic volume. It uses both a supply duct system and an exhaust duct system to uniformly distribute supply air and collect vitiated air throughout the tunnel length (Figure 4). 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, while 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

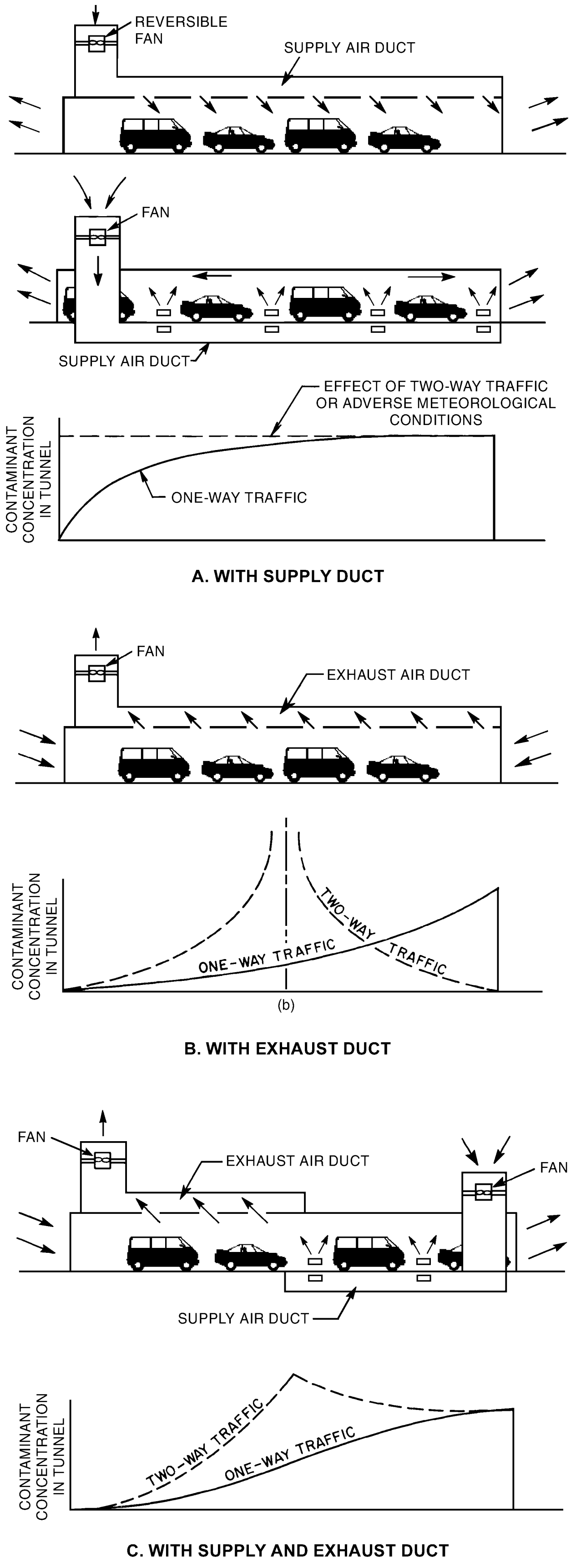

Fig. 3 Semitransverse Ventilation

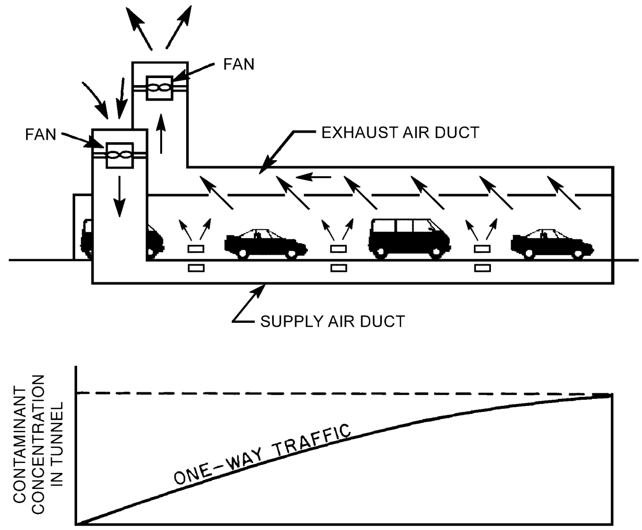

Fig. 4 Full Transverse Ventilation

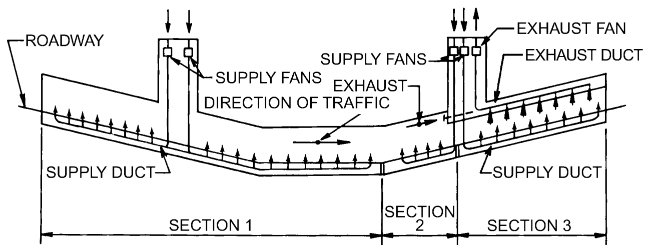

Fig. 5 Combined Ventilation System

and be extracted by the exhaust system without mixing, and allows fresh air to enter through the portals, which creates a respirable 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.

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 5 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 100 to 300 ft^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. 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. 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 (EPA 2002). In contaminant emission rate analyses, the following practices and assumptions may be implemented:

- 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 2 presents typical physical data for automobiles for use in normal ventilation air quantity analyses.

Allowable Carbon Monoxide

In 1975, the EPA issued a supplement to its *Guidelines for Review of Environmental Impact Statements* concerning the concentration of CO in tunnels. This supplement evolved into a design approach based on keeping CO concentration at or below 125 ppm, for a maximum 1 h exposure time, for tunnels located at or below an altitude of 3280 ft. In 1989, the EPA revised its recommendations for maximum CO levels in tunnels located at or below an altitude of 5000 ft to the following:

- A maximum of 120 ppm for 15 min exposure
- A maximum of 65 ppm for 30 min exposure
- A maximum of 45 ppm for 45 min exposure
- A maximum of 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 5000 ft, 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 5000 ft.

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.

Table 2 Average Dimensional Data for Automobiles Sold in the United States

Size/Class	Wheelbase, ft	Length, ft	Frontal Area, ft^2
Subcompact	8.0	14.0	17.3
Compact	9.0	15.9	19.8
Midsize	9.7	18.0	21.9
Large	10.0	18.5	22.4
Average	9.18	16.60	20.35

Computer Programs

SES. The Subway Environment Simulation (SES) program can be used to examine longitudinal airflow in a road tunnel (DOT 1997). SES, a one-dimensional network model, is the predominant worldwide tool used to evaluate longitudinal airflow in tunnels.

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 highway 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 will need to update emissions data for the calendar year of interest. The program is available from NTIS (1980).

CFD. Computational fluid dynamics software can model normal operating conditions in road tunnels and predict the resulting contaminant concentration levels; however, the complexity of the modeling and the amount of detail in the results may exceed that desired by the engineer.

EMERGENCY VENTILATION AIR QUANTITIES

A road tunnel ventilation system must be able to protect the traveling public during the most adverse and dangerous conditions, 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 100 cfm per lane-foot. 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.

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

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

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

where

V_C = critical velocity, ft/s
T_F = average temperature of fire site gases, °R
K_1 = 0.606
K_G = grade factor (see Figure 6)
g = acceleration caused by gravity, ft/s^2
H = height of duct or tunnel at fire site, ft
q = heat that fire adds directly to air at fire site, Btu/s
ρ = average density of approach (upstream) air, lb/ft^3
c_P = specific heat of air, Btu/lb·°R
A = area perpendicular to flow, ft^2
T = temperature of approach air, °R

Fire Size. The fire size selected for design significantly affects the magnitude of the critical velocity needed to prevent backlayering. Table 3 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 4 provide guidance in selecting design exposure temperatures for ventilation equipment. NFPA *Standard* 130 provides further information.

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.

Computer Programs

SES. This program contains a fire model that can determine how much longitudinal airflow is required to overcome backlayering and control smoke movement in a tunnel.

CFD. 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.

Table 3 Typical Fire Size Data for Road Vehicles

Cause of Fire	Equivalent Size of Gasoline Pool, ft^2	Fire Heat Release Rate, 10^6 Btu/h	Smoke Generation Rate, 1000 cfm	Maximum Temperature,* °F
Passenger car	22	≈17	42	750
Bus/truck	86	≈68	127	1290
Gasoline tanker	300 to 1100	≈340	200 to 400	1830

Source: PIARC (1995).
*Temperature 30 ft downwind of fire with minimum air velocity necessary to prevent backlayering.

Table 4 Maximum Air Temperatures Experienced at Ventilation Fans During Memorial Tunnel Fire Ventilation Test Program

Nominal FHRR, 10^6 Btu/h	Temperature at Central Fans,[a] °F	Temperature at Jet Fans,[b] °F
68	225	450
170	255	700
340	325	1250

[a]Central fans located 700 ft from fire site.
[b]Jet fans located 170 ft downstream of fire site.

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, and has been validated against data from MHD/FHWA (1995).

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 (1999) 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:

$$FVP = VP_2 \qquad (3)$$

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

$$FSP = FTP - FVP \qquad (4)$$

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.

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

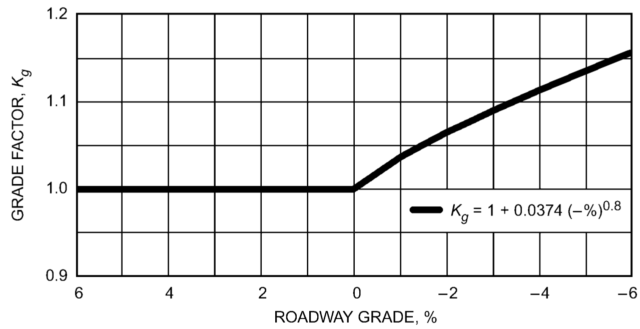

Fig. 7 Roadway Grade Factor

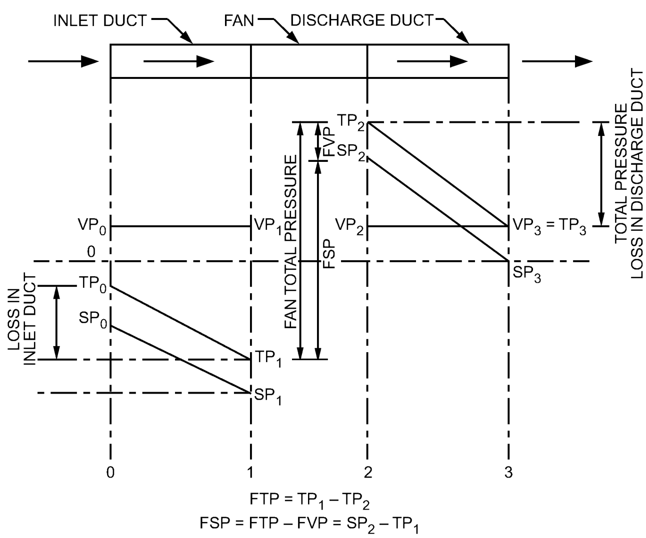

Fig. 6 Fan Total Pressure

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

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

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**

$$P_T = P_1 + \left(\frac{12\rho_a}{\rho_w g_c}\right)\left\{\frac{V_o^2}{2}\left[\frac{\alpha L Z^3}{3H} - (1-K)\frac{Z^2}{2}\right] + \frac{\beta L Z}{2H^3}\right\} \quad (7)$$

Static pressure loss for an **exhaust duct**

$$P_S = P_1 + \left(\frac{12\rho_a}{\rho_w g_c}\right)\left\{\frac{V_o^2}{2}\left[\frac{\alpha L Z^3}{(3+c)H} + \frac{3Z^2}{(2+c)}\right] + \frac{\beta L Z}{2H^3(1+c)}\right\} \quad (8)$$

where

P_T = total pressure loss at any point in duct, in. of water
P_S = static pressure loss at any point in duct, in. of water
P_1 = pressure at last outlet, in. of water
ρ_a = density of air, lb/ft^3
ρ_w = density of water, lb/ft^3
V_o = velocity of air entering duct, ft/s
L = total length of duct, ft
X = distance from duct entrance to any location, ft
Z = $(L - X)/L$
H = hydraulic radius, ft
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 = 0.01433 ft^4/s^2
c = constant relating to turbulence of exhaust port
= 0.20 for exhaust rates less than 200 cfm per foot
= 0.25 for exhaust rates greater than 200 cfm per foot
g_c = gravitational constant = 32.2 $lb_m \cdot ft/lb_f \cdot s^2$

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 34 of the 2001 *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. 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 the 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 accuracy of the instrument. The length of piping between the sampling point and the 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 if 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 in 100 ft of 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.

The 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 (such as 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 allows 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 being 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 the hardwired systems used 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.

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. The 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 25 ppm of CO for an 8 h exposure. The OSHA standard (Code of Federal Regulations 29 CFR 1910, subpart Z) is 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 35 ppm and a maximum level of 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. The 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% outside 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 the 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 the 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 the 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 the floor level (such as electric forced air heaters, electric radiant heating, or 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 12, Air Contaminants, of the 2001 *ASHRAE Handbook—Fundamentals* and Chapter 24, Air Cleaners for Particulate Contaminants, in the 2000 *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% outside 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% outside 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-water, chilled-water, or secondary water service are 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.

PARKING GARAGES

Automobile parking garages can be either fully enclosed or partially open. Fully enclosed parking areas are usually 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 model codes, ANSI/ASHRAE *Standard* 62, and its predecessor standards have recommended a flat exhaust rate of either 1.5 cfm/ft^2 or 6 air changes per hour (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 1.5 cfm/ft^2 was satisfactory. However, local codes may still require 1.5 cfm/ft^2 or 6 ACH, so the engineer may be required to request a variation, or waiver, from authorities having jurisdiction before implementing a lesser ventilation system design. NFPA 88A recommends a minimum of 1.0 cfm/ft^2.

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

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 25 ppm for an 8 h exposure, and the U.S. EPA has determined that exposure, at or near sea level, to a CO concentration of 35 ppm for up to 1 h is acceptable. For parking garages more than 3500 ft above sea level, more stringent limits are required. In Europe, an average concentration of 35 ppm and a maximum level of 200 ppm are usually maintained in parking garages.

Because various agencies and countries differ on the acceptable level of CO in parking garages, a reasonable solution is a ventilation rate designed to maintain a CO level of 35 ppm for 1 h exposure, with a maximum of 120 ppm, or 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, 35 ppm is considered to be an acceptable level of exposure.

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, it usually ranges from 60 to 180 s. Table 5 lists approximate data for average vehicle entrance and exit times; this data should be adjusted to suit the specific physical configuration of the facility.

Car Emission Rate

Operating a car engine 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 6. 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.

Table 5 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 6 Predicted CO Emissions in Parking Garages

	Hot Emission (Stabilized), lb/h		Cold Emission, lb/h	
Season	**1991**	**1996**	**1991**	**1996**
Summer, 90°F	0.336	0.250	0.565	0.484
Winter, 32°F	0.478	0.447	2.744	2.508

Results from EPA MOBILE3, version NYC-2.2 (1984); sea level location.
Note: Assumed vehicle speed is 5 mph.

Design Method

To determine the design airflow rate required to ventilate an enclosed parking garage, the following procedure can be followed:

Step 1. Collect the following data:

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

Step 2. (1) Determine the peak CO generation rate per unit floor area G, in lb/h·ft^2, for the parking garage:

$$G = NE/A_f \tag{9}$$

(2) Normalize the peak CO generation rate using the reference value $G_0 = 5.46 \times 10^{-3}$ lb/h·ft^2 and Equation (10). This reference value is based on an actual enclosed parking facility (Krarti and Ayari 1998):

$$f = 100G/G_0 \tag{10}$$

Step 3. Determine the minimum required ventilation rate per unit floor area (Q) using Figure 8, or the correlation presented by Equation (11), depending on the maximum level of CO (CO_{max}):

$$Q = Cf\theta \tag{11}$$

where

$C = 2.370 \times 10^{-4}$ cfm/ft^2·s for CO_{max} = 15 ppm
$C = 1.363 \times 10^{-4}$ cfm/ft^2·s for CO_{max} = 25 ppm
$C = 0.948 \times 10^{-4}$ cfm/ft^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 90,000 ft^2, and an average height of 9 ft. The total length of time for a typical car operation is 2 min (120 s). Determine the required ventilation rate for the enclosed parking garage in cfm/ft^2 and in ACH 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.

Step 1. Garage data:

N = 450 × 0.4 = 180 cars
E = 1.544 lb/h, the average of all values of emission rate for a winter day, from Table 6
CO_{max} = 25 ppm
θ = 120 s

Step 2. Calculate the normalized CO generation rate:

$G = (180 \times 1.544 \text{ lb/h})/90{,}000 \text{ ft}^2 = 3.09 \times 10^{-3}$ lb/h·ft^2
$f = 100 \times (3.09 \times 10^{-3} \text{ lb/h·ft}^2) / 5.46 \times 10^{-3} \text{ lb/h·ft}^2 = 56.6$

Step 3. Determine the ventilation requirement, using Figure 8 or the correlation of Equation (11) for CO_{max} = 25 ppm.

$Q = 1.363 \times 10^{-4} \text{ cfm/s·ft}^2 \times 56.6 \times 120 \text{ s} = 0.93$ cfm/ft^2

Or, in air changes per hour:

ACH = (0.93 cfm/ft^2 × 60 min/h)/9 ft = 6.2

Notes:

1. If the average vehicle CO emission rate is reduced to E = 0.873 lb/h, due, for instance, to better emission standards or better maintained cars, the required minimum ventilation rate decreases to 0.52 cfm/ft^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. Figure 9 shows the maximum CO level in a tested parking garage (Krarti et al. 1998) for three car movement profiles (as illustrated in Figure 10) 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 9 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 25 ppm. Wear and tear and maintenance on mechanical and electrical equipment are reduced with a CO-based demand strategy.

Figure 10 is based on maintaining a 25 ppm CO level. With most systems, actual energy usage is further reduced if 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 outside air openings are used to draw in ventilation air, or if infiltration is permitted, 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 outside 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, the wall openings or free area should be as large as possible. Part of the free area should be at floor level.

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.

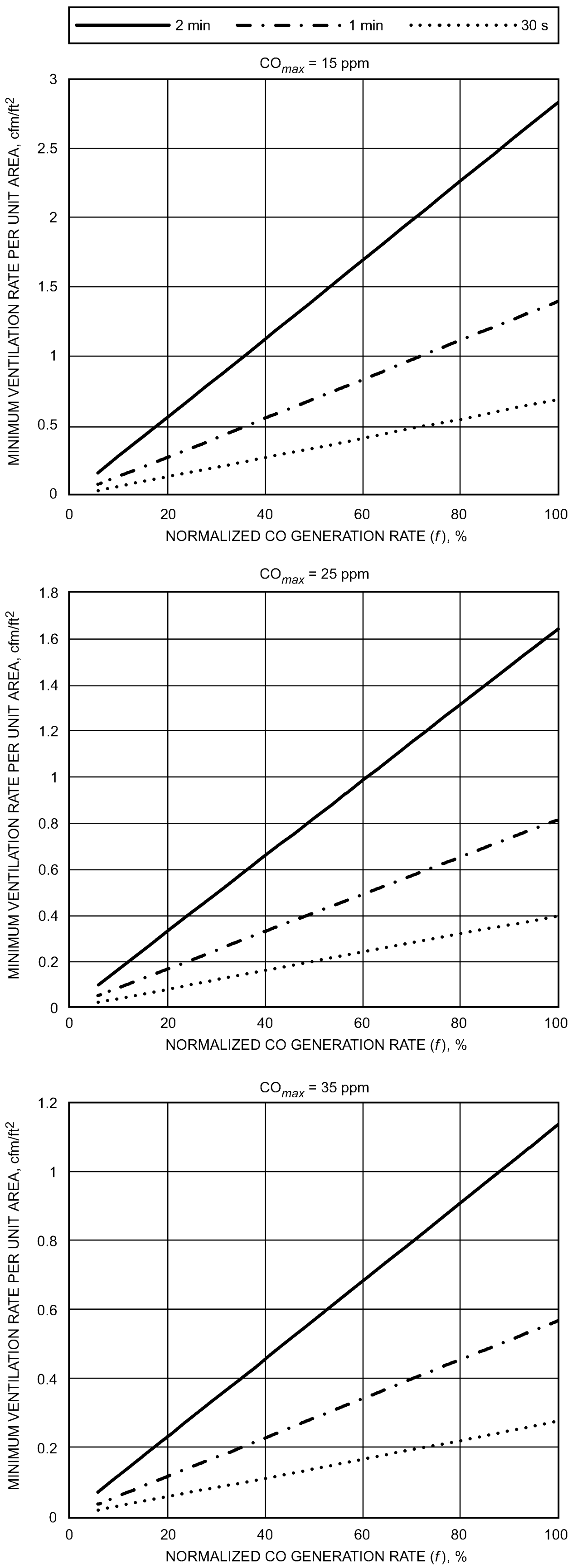

Fig. 8 Ventilation Requirement for Enclosed Parking Garage

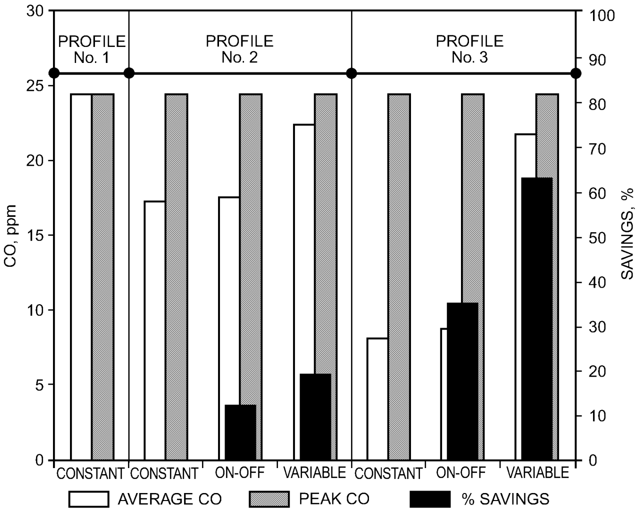

Fig. 9 Typical Energy Savings and Maximum CO Level Obtained for Demand CO-Ventilation Controls

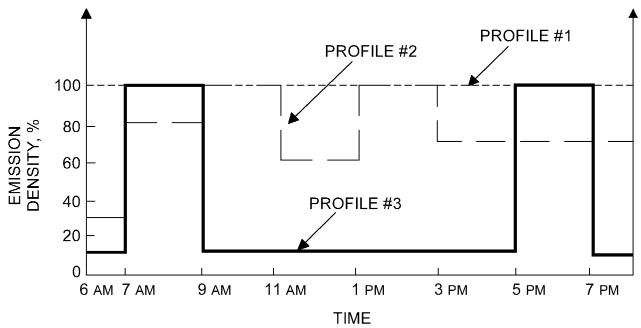

Fig. 10 Three Car Movement Profiles

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

The air exhausted from a parking garage should meet state and local air pollution control requirements.

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 such factors as the local climate, the size of the bus fleet, and the type of fuel used by the buses. Bus servicing and storage areas may be located outside 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% outside air with no recirculation. Therefore, using heat recovery devices should be considered for bus garages 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 and most model codes recommend minimum outdoor air ventilation of 1.5 cfm per square foot of floor area in vehicle repair garages, with no recirculation. 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 the 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* 88B recommends a minimum of one air change every five minutes (i.e., 12 ACH) 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 600 cfm 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 500°F 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 2.25 cfm per square foot of room area at floor level to remove acid vapors, and 0.75 cfm per square foot 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 100 fpm 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 30 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 and several model codes recommend a ventilation air minimum of 1.5 cfm per square foot whereas NFPA *Standard* 30A recommends 1 cfm per square foot, but not less than 150 cfm total. The designer should determine which minimum volume of ventilation air is applicable, based on the local code adopted. However, additional ventilation may be necessary: during a service cycle, buses often queue up in

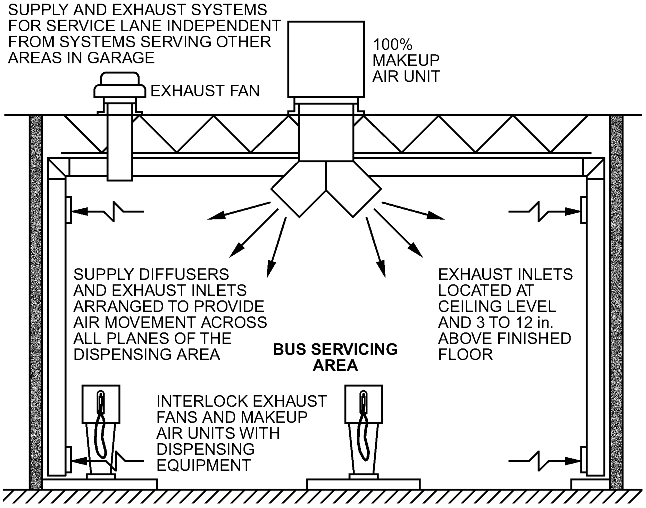

Fig. 11 Typical Equipment Arrangement for Bus Garage

the service lane with their engines running. Depending on the queue length and service time for each bus, contaminant levels may exceed maximum allowable concentrations. Volumetric analysis examining contaminant generation should therefore be considered.

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 3 to 12 in. 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 11.

Another common feature of modern service lanes is the cyclone cleaning system, which is used to vacuum out the interior of a bus. 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 outside and provide untempered makeup air through relief hoods above the service lane.

STORAGE AREAS

Where buses are stored inside, the minimum ventilation standard of 1.5 cfm per square foot should be provided, 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 8 ft above the finished floor or, where located in active trafficways, 2 ft 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 18 in. 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 the 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 the 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. Such fuels include methanol, ethanol, hydrogen, 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 of such literature is the Alternative Fuels Data Center at the U.S. Department of Energy in Washington, D.C.

For CNG bus facilities, NFPA *Standard* 52 recommends a separate mechanical ventilation system providing at least 1 cfm per 12 ft^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 one-fifth the lower flammability limit 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.

DOT (1996) 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 air changes per hour, 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 800°F. 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.

For LNG bus facilities, the only published recommendations are in NFPA *Standard* 57, which is limited to bus fueling areas. The standard recommends a separate mechanical ventilation system providing at least 1 cfm per 12 ft^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 one-fifth the lower flammability limit is present. Fueling equipment should be interlocked to shut down in case the mechanical ventilation system fails.

NFPA *Standard* 58 is the only document that contains provisions relating specifically to LPG-fueled buses. This standard prohibits 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, provided they are not parked near sources of heat, open flames (or similar sources of ignition), or "inadequately ventilated" pits. The standard does not recommend a ventilation rate for bus repair and storage facilities, but it does recommend a minimum of 1 cfm per square foot in buildings and structures housing LPG distribution facilities.

No U.S. standards relate specifically to hydrogen-powered vehicles. NFPA *Standard* 50A provides general recommendations for point-of-use gaseous hydrogen systems, and gives limited guidance.

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, 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 10 ft^2 per person and, during periods of extreme congestion, 3 to 5 ft^2 per person.

The choice between a natural ventilation system and a mechanical ventilation system 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 permit 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 12 and 13.

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

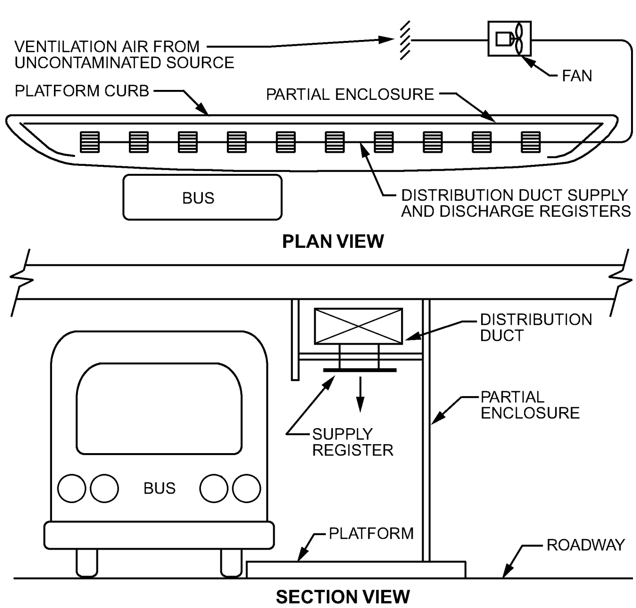

Fig. 12 Partially Enclosed Platform, Drive-Through Type

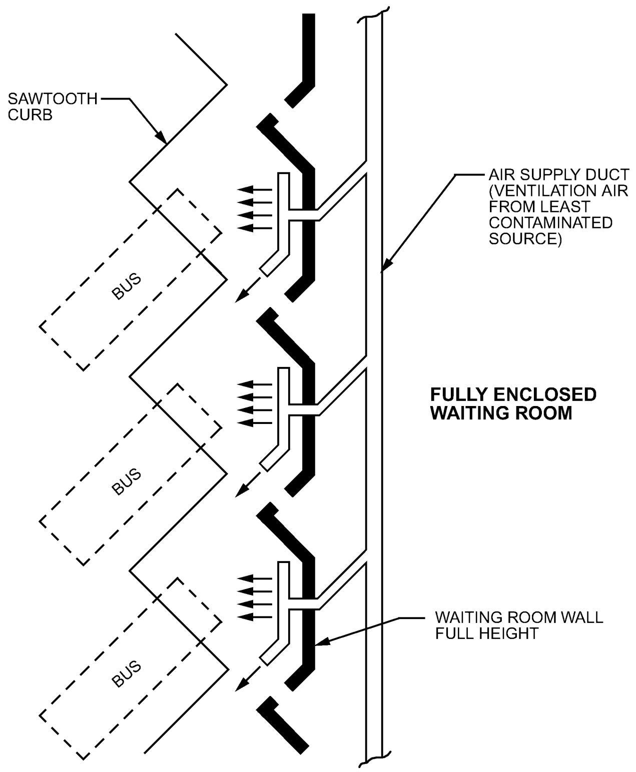

Fig. 13 Fully Enclosed Waiting Room with Sawtooth Gates

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 250 fpm to avoid drafts on the platform. Partially enclosed platforms require large amounts of outside air to hinder fume penetration; experience indicates that a minimum of 17 cfm per square foot of platform area is typically required during rush hours, and about half this rate is required during other periods. Figure 12 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 13 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 operations. 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 for each gate to dilute local contaminants to acceptable levels.

Table 7 8 Hour, 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)	5.0	2.0

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

Table 8 EPA Emission Standards for Urban Bus Diesel Engines

	Emissions, lb/min·bhp × 10^{-5}			
Model Year	Hydrocarbons (HC)	Carbon Monoxide (CO)	Oxides of Nitrogen (NO_x)	Particulate Matter (PM)
1991	4.78	57.0	18.4	0.919
1993	4.78	57.0	18.4	0.368
1994	4.78	57.0	18.4	0.257
1996	4.78	57.0	18.4	0.184*
1998 to 2003	4.78	57.0	14.7	0.184*
2004 to 2006	4.78	57.0	7.35 to 9.19	0.184
2007 and later	0.515	57.0	0.074	0.037

*In-use PM standard 0.257 × 10^{-5} lb/min·bhp

BUS OPERATION AREAS

Ventilation for bus operation areas should be designed and evaluated to maintain engine exhaust contaminant concentrations in 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 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 7 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.

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 8 (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. The current recommended version is MOBILE5B (1994), but MOBILE6 (2002), will be used in the near future. 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 outside 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 U.S. Department of Transportation's Federal Transit Administration (FTA) and the NFPA.

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 1003°F 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 3600 psig and 70°F. 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 will 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 (1998) recommends a blanket rate of 5 ACH in fueling areas. FTA 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 minimum gas contaminant levels must be maintained during the hours of occupancy.

RAPID TRANSIT

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 are among the conditions that 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* (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 according to schedule, and passengers traveling smoothly through the stations to and from transit vehicles. During normal operations, 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 an 84°F station from 90°F 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 will adjust to the new environment and produce 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. The Relative Warmth Index (RWI) quantifies this transient effect, allowing the designer to select an appropriate design air temperature for the station based on the transient sensation of comfort, rather than the steady-state sensation of comfort. Design temperatures based on the transient approach are typically higher (often 5 to 9°F) 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 free flow 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 the continued operation of train air conditioning units. The aim of forced ventilation is to maintain onboard passenger comfort during congestion.

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 train operations 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 an undesirable heat build-up in the station.

To counter the negative effects of short-circuiting airflow, ventilation shafts are customarily located near the 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 be departing trains. Relief shafts also induce outside 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 cooler outside 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 outside 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.

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 14).

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

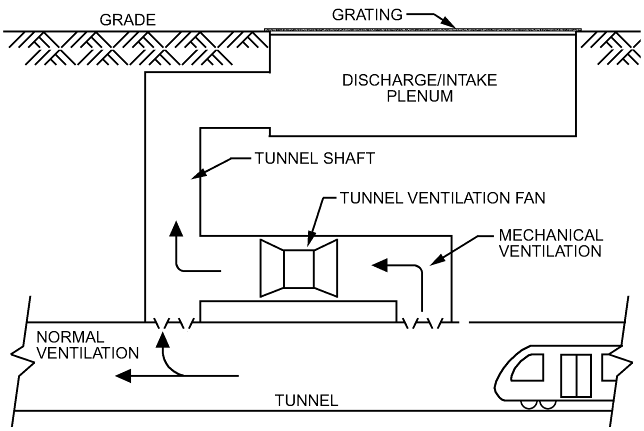

Fig. 14 Tunnel Ventilation Shaft

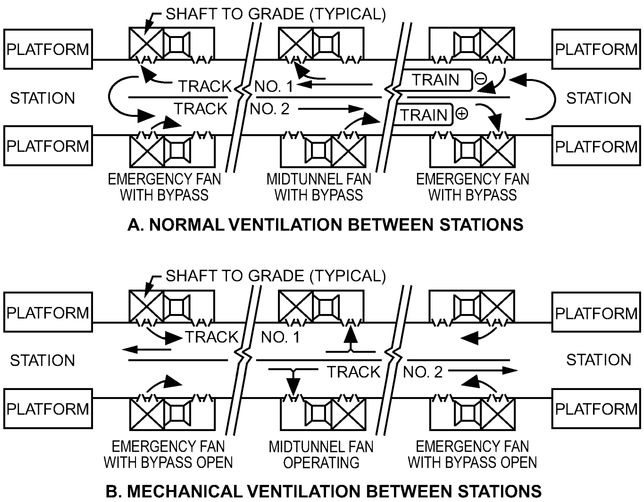

Fig. 15 Tunnel Ventilation Concept

Figure 15 shows a typical tunnel ventilation system between two subway stations. Here the flow of warm tunnel air into the station is minimized by either normal or mechanical ventilation effects. In Figure 15A, the 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 15B shows an alternative operation with the same ventilation system where midtunnel 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 would be closed, and makeup air for the mid-tunnel exhaust fans would enter through station entrances.

A more direct mechanical ventilation system (Figure 16) 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 16A, 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 16B), also known as an underplatform exhaust (UPE) system, is the least effective alternative for heat removal. With a UPE system, a quantity of air equal to that withdrawn by the underplatform exhaust enters the station control volume, either

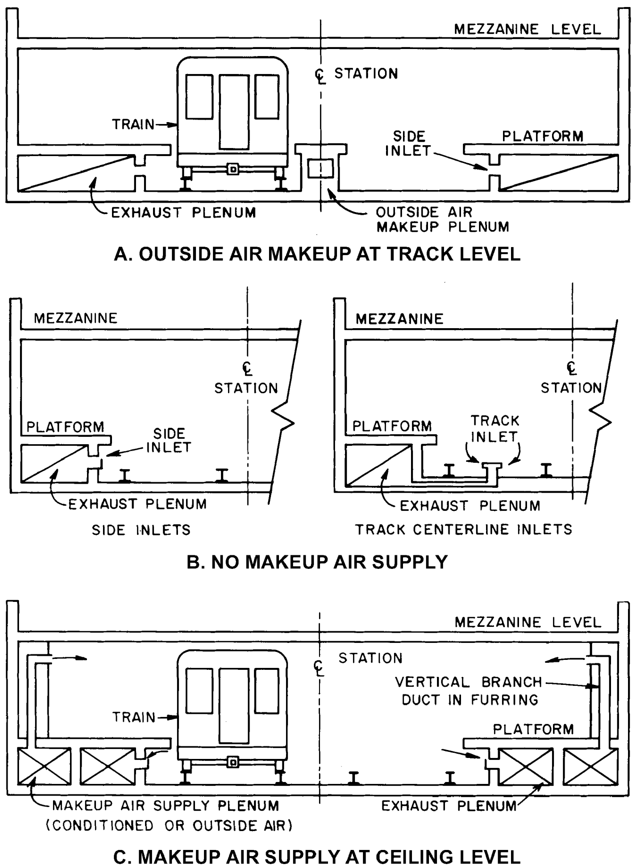

Fig. 16 Trackway Ventilation Concept (Cross-Sections)

from outside or from the tunnels. When the ambient, or tunnel, air temperature is higher than the station design air temperature, a UPE system reduces the station heat load by removing undercar heat, but it also increases the station heat load by drawing in warmer air, which may affect platform passenger comfort.

Figure 16C 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.

Emergency Ventilation

During a subway tunnel fire, mechanical ventilation is a major part of the response and smoke control strategy. Fires induce the airflow required to support combustion and growth. Activating an emergency fan system increases the air supply over that required for combustion and tends to reduce the progression of the fire by lowering the flame temperature, but it also generates additional smoke because the percentage of incomplete combustion is increased. More importantly, an emergency ventilation system should be implemented in a subway system to control the direction of smoke migration and permit safe evacuation of passengers and access by firefighters (see NFPA *Standard* 130 and the section on Road Tunnels).

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, outside 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 (see Figure 17).

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 advanced 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 from the central console to establish smoke flow control.

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

The possibility of a fire on the station platform or in another public area should also be considered. Such 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. Typical fire size data for single transit vehicles are as follows:

- Older transit vehicle ≈ 50×10^6 Btu/h
- New, hardened vehicle ≈ 35×10^6 Btu/h
- Light rail vehicle ≈ 30×10^6 Btu/h

Because 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) 2002].

Station Air Conditioning

Faster station approach speeds and closer headways, both made possible by computerized train control, have increased the 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 50 mph, may reach 5.0×10^6 Btu/h, even after some tunnel heat is removed by the heat sink, station underplatform exhaust system, and tunnel ventilation system. To remove this heat from a station with a ventilation system using outside air and a maximum air temperature increase of 3°F, for example, would require roughly 1.4×10^6 cfm of outside 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 outside air loads (based on a station design air temperature 7°F lower than ambient), could be handled by about 630 tons 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.

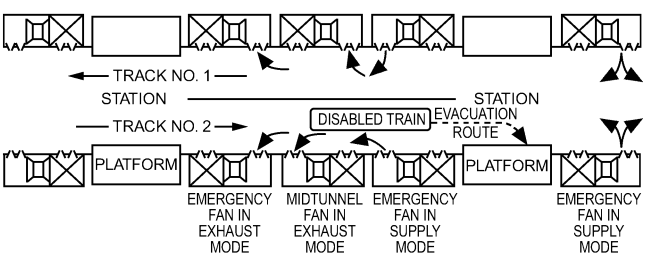

Fig. 17 Emergency Ventilation Concept

Conversely, where the train length equals platform length and the ceiling height above the platform is limited to 10 to 11.5 ft, isolating heat sources and using spot cooling are usually not feasible.

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 train operations and one for emergency fire/smoke operations. Criteria for normal operations include limits on tunnel air temperature 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, underplatform exhaust, and station air conditioning.

Train propulsion/braking systems and the 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* (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 outside air conditions and thermal conditions in the transit vehicles. For passenger comfort, the preferred air velocity is between 500 and 1000 fpm 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 outside 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 outside 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 to have a minimum of 15 cfm outside 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 onboard passengers' ears and sinuses. Based on nuisance factor criteria, if the total change in the air pressure is greater than 2.8 in. of water, the rate of static pressure change should be kept below 1.7 in. of water per second. 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 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 minimum air velocity is provided in DOT (1976). The maximum tunnel air velocity experienced by evacuating passengers should not exceed 2200 fpm.

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

Table 9 Typical Heat Source Emission Values

Source of Heat	Heat Rejection, Btu/h
Train A/C system (per vehicle)	144,000
Escalator (10 hp, 75% load factor)	19,100[a]
Fare collection machine	2730 [a]
Station lighting	10.2 per square foot [a]
People (walking, standing)	250 sensible[b]
	250 latent[b]

[a]See Subway Environmental Design Handbook, Part 3 (DOT 1976).
[b]See 2001 *ASHRAE Handbook—Fundamentals*, Chapter 29.

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 10 tons per vehicle for shorter rail cars (about 50 ft long), up to about 20 tons for longer rail cars (about 70 ft 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 outside 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 9.

Heat Sink

The amount of heat flow from the tunnel air to subway walls varies seasonally, as well as for morning and evening rush-hour operations. Short periods of abnormally high or low outside 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 the soil type (dense rock or light, dry soil), the extent of migrating groundwater or the local water table, and the surface configuration of the 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. The 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%.

An **underplatform exhaust (UPE)** system, described in the section on Mechanical Ventilation, uses a hood to remove heat generated by vehicle underfloor equipment (e.g., resistors, air-conditioning condensers) from the station environment. DOT (1976) provides a table (based on field test results) of various UPE airflow rates versus UPE system efficiency. 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.

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 impact of cooling dumping on the 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 1000 to 6000 hp. 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 (see Figure 18).

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 the heat 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.

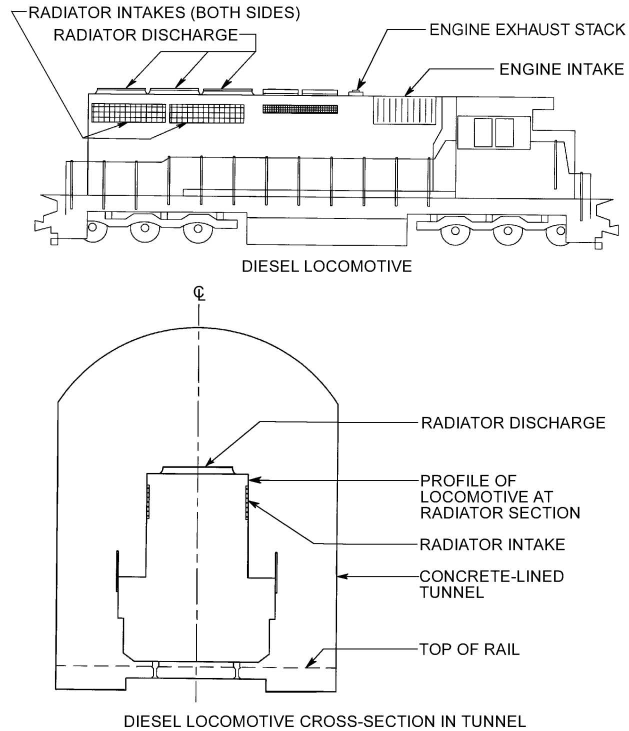

Fig. 18 Typical Diesel Locomotive Arrangement

DESIGN CONCEPTS

Most long railroad tunnels (over 5 mi), 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, the environmental and structural site constraints, and the train traffic flow. One design, for a 9 mi long tunnel (Levy and Danziger 1985), extended the basic concept by including a midtunnel door and a partitioned shaft, which was connected to the tunnel on both sides of the midtunnel door. The combination of the midtunnel door and the 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, the relatively low speed of the trains, and the 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:

$$q_M = FH - q_S - q_R - P_G \tag{12}$$

where

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

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

$$q_G = (P_G - L_A)(1 - \varepsilon_G) \tag{13}$$

where

q_G = main generator heat loss, Btu/h
L_A = power driving locomotive auxiliaries, Btu/h
ε_G = main generator efficiency

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

$$q_{TM} = P_G - L_A - q_G - P_{TE} \tag{14}$$

where

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

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

$$q_T = q_S + q_R + q_m + L_A + q_G + q_{TM} \tag{15}$$

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

$$t_{AN} = t_{AT} + \frac{q_T(N-1)}{\rho c_p Q_R} \tag{16}$$

where

t_{AN} = average tunnel air temperature approaching Nth locomotive, °F
t_{AT} = average tunnel air temperature approaching locomotive consist, °F
ρ = density of tunnel air approaching locomotive consist, lb/ft^3
c_p = specific heat of air, Btu/lb$_m$·°F
Q_R = tunnel airflow rate relative to train, ft^3/h

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 115°F. Field tests in operating tunnels (Aisiks and Danziger 1969; Levy and Elpidorou 1991) have shown, however, that some units can operate continuously with radiator inlet air temperatures as high as 135°F. 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 such variables 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 20 mph, Levy and Elpidorou (1991) showed that a reasonable estimate is to assume the radiator inlet air temperature to be about 10°F higher than the average air temperature approaching the unit. For trains moving at 30 mph 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 (1997), relates the piston effect of the train, the steady-state airflow from the fans to the tunnel, and the pressure across the tunnel door. This expression assumes that air leakage across the tunnel door is negligible. Figure 19 shows the dimensional variables on a schematic of a typical tunnel.

$$\frac{\Delta p}{32.2\rho} = \frac{(p_A - p_B)}{32.2\rho} - \frac{Hg}{g_C} + \left(\frac{(A_V^2 + A_V A_T C_{DVB})}{(A_T - A_V)^2} + \frac{A_V C_{DVF}}{A_T}\right)\frac{(A_T V + Q_S)^2}{2A_T^2 g_C} + \frac{f_T L_V P_T (A_V V + Q_S)^2}{8(A_T - A_V)^3 g_C} + \frac{\lambda_V L_V P_V (A_T V + Q_S)^2}{8(A_T - A_V)^3 g_C} + \frac{f_T (L_T - L_V) P_T Q_S^2}{8A_T^3 g_C} + \frac{K Q_S^2}{2A_T^2 g_C} \tag{17}$$

where

Δp = static pressure across tunnel door, lb_f/ft^2
ρ = density of air, lb_m/ft^3
p_A = barometric pressure at Portal A, lb_f/ft^2
p_B = barometric pressure at Portal B, lb_f/ft^2
H = difference in elevation between portals, ft
g = acceleration of gravity = 32.2 ft/s^2
g_C = gravitational constant = 32.2 $ft \cdot lb_m/lb_f \cdot s^2$
A_V = train cross-sectional area, ft^2
A_T = tunnel cross-sectional area, ft^2
C_{DVB} = drag coefficient at back end of train
C_{DVF} = drag coefficient at front end of train
V = velocity of train, ft/s
Q_S = airflow delivered by fan, ft^3/s
f_T = tunnel wall friction factor
L_T = tunnel length, ft
L_V = train length, ft
P_T = tunnel perimeter, ft
P_V = train perimeter, ft
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

$$Q_{rel} = A_T V + Q_S \tag{18}$$

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

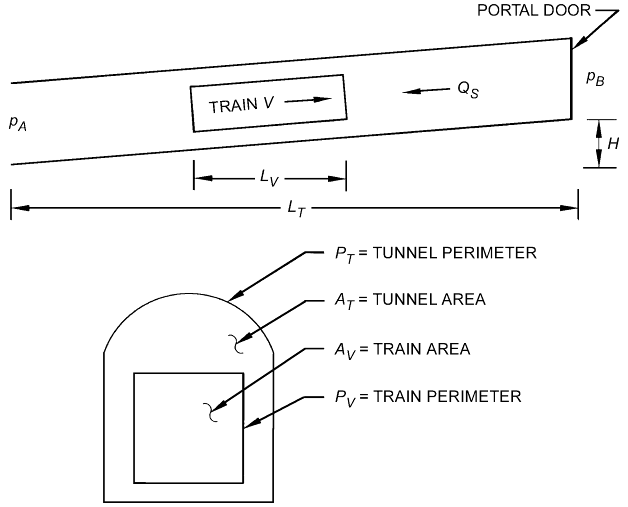

Fig. 19 Railroad Tunnel Aerodynamic Related Variables

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 mi 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.

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 outside 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.

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 aid in removal of fumes and contaminants. Ventilation should be accomplished using 100% outside air, with no recirculation. 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.

MAINTENANCE AND REPAIR AREAS

ANSI/ASHRAE *Standard* 62 and most model codes require a minimum outdoor air ventilation rate of 1.5 cfm/ft^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 1.5 cfm/ft^2 ventilation rate as a blanket standard. The section on Contaminants has 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 6000 hp) 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. 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. 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 2001) notes that 6 ACH is usually sufficient to provide adequate dilution for both idling locomotives and short engine runs at high speed. Ventilation design should take advantage of thermal buoyancy by removing hot exhaust gases at a high point in the shop, before they cool and drop to the floor. Locomotive radiator cooling fans recirculate the cooled gases, making them more difficult to remove. Makeup air should be introduced into the shop at floor level and tempered as needed.

Shops in colder climates should be heated both for the comfort of workers 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. Usually, air curtains or door heaters are not needed because shop doors are opened infrequently.

ENCLOSED SERVICING AREAS

Although most locomotive servicing is done outside, 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 2001), the air temperature at the exhaust source will be between 350 and 950°F. A typical ventilation design could have hoods approximately 18 to 23 ft above the top of the rail, with throat velocities between 30 and 36.7 fps. For dilution ventilation, the designer should perform a volumetric analysis of contaminant generation and air exchange rates.

CONTAMINANTS

The components of diesel engine exhaust gases that affect the ventilation system design are oxides of nitrogen (NO_x), hydrocarbons (HC), formaldehyde, sulfur dioxide (SO_2), odor constituents, aldehydes, smoke particles, and carbon monoxide (CO). Operating diesel engines in enclosed spaces also reduces visibility and creates odors. A diesel locomotive that has been operating, lightly loaded, for several minutes often produces large amounts of visible smoke and emissions from accumulated unburned fuel.

Except for the engine emissions data, information in the section on Bus Operation Areas applies to diesel locomotive facilities. The *Tunnel Engineering Handbook* (Bendelius 1996) notes that all exhaust gas contaminants can be maintained within acceptable limits as long as NO_x levels are maintained within specified limits. Table 10 provides approximate data for contaminants found in engine exhaust gases of a typical diesel locomotive, as well as other design information. The designer should consult the manufacturers of the applicable locomotive engines for each project for the most current engine data.

EQUIPMENT

The ability of an enclosed vehicular facility to function depends mostly on the effectiveness and reliability of its ventilation system,

Table 10 Sample Diesel Locomotive Engine Emission Data[a]

Throttle Position (Notch)	Engine Speed, rpm	Engine Power, bhp	Engine Airflow,[b] cfm	Fuel Rate, lb/h	NO_x, lb/h	CO, lb/h	HC, lb/h	SO_2, lb/h	Particulates, lb/h
Four-Stroke Cycle, With Head End Power (HEP)									
8, Freight	1050	3268	8816	1103	81	5.9	3.9	0.51	0.96
7, HEP	900	2771	7068	929	71	13	3.0	0.43	1.1
6, HEP	900	2254	5668	762	62	11	2.6	0.35	0.92
5, HEP	900	1777	4433	609	51	10	1.6	0.28	0.64
4, HEP	900	1023	2677	369	34	3.2	1.2	0.17	0.51
3, HEP	900	713	2055	266	22	2.3	0.94	0.12	0.49
2, HEP	900	431	1656	174	14	1.6	0.88	0.08	0.54
1, HEP	900	322	1651	144	13	1.6	0.92	0.07	0.65
HEP idle	900	185	1511	81	6.3	2.0	1.1	0.04	0.91
Standby	720	512	1441	189	16	1.9	0.81	0.09	0.65
High idle	450	34	466	23	1.9	0.49	0.40	0.01	0.13
Low idle	370	22	NA[c]	17	1.1	0.70	0.35	0.01	0.10
Two-Stroke Cycle, No Head End Power (HEP)									
8	903	3210	8880	1060	86	8.1	2.0	0.49	1.5
7	821	2540	7100	833	56	4.1	1.2	0.38	0.97
6	726	1700	5310	572	38	1.5	0.85	0.26	0.64
5	647	1390	4630	480	33	1.4	0.79	0.22	0.58
4	563	1060	3950	368	28	0.61	0.64	0.17	0.42
3	489	714	3410	254	24	0.42	0.51	0.12	0.30
2	337	370	2200	142	13	0.46	0.33	0.07	0.12
1	337	207	2270	91	7.7	0.34	0.25	0.04	0.07
High idle	339	14	2390	32	2.5	0.17	0.21	0.02	0.05
Low idle	201	10	1320	14	1.3	0.08	0.08	0.01	0.02
Auxiliary Engine/Alternator for Head End Power (HEP)									
N/A	1800	699	1930	275	17	7.3	0.69	0.13	0.37
N/A	1800	566	2190	226	17	1.1	0.78	0.10	NA[c]
N/A	1800	438	2010	179	13	0.53	0.67	0.08	0.26
N/A	1800	377	1900	157	10	0.39	0.61	0.07	0.25
N/A	1800	305	1810	135	8.4	0.39	0.56	0.06	0.23
N/A	1800	238	1710	114	6.5	0.40	0.57	0.05	0.20
N/A	1800	173	1640	95	4.8	0.41	0.55	0.04	0.18
N/A	1800	31	1480	55	2.2	0.46	0.60	0.03	0.16

[a]Data from SwRI, Southwest Research Institute Report 08-4976 (1992). [b]Intake, corrected to standard air density 0.0751 lb/ft^3. [c]Data not available.

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, 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 should 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, no matter how many fans are operating, falls well below the unstable performance range. 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.

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 20.

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 100 fan diameters apart so that the jet velocity does not affect the 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.

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 three

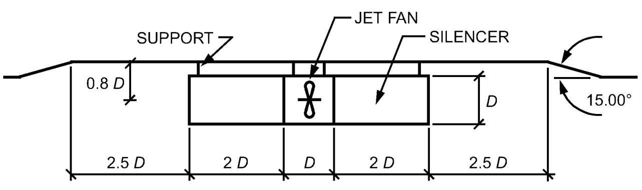

Fig. 20 Typical Jet Fan Arrangement in Niche

months 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. Fans with multispeed motors should be operated at all speeds.

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 four reversal cycles per year for 50 years 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.

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.

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 0.005 in. per foot 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 0.005 in. per foot 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. 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.

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.

Centrifugal fans. 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
- That the dBA rating at certain 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 level down to an acceptable value if measured sound values exceed the specified maximum
- 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 the 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 4 to 50 in. of water.

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, tunnel length, clearance between the 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., if a train operates at high speed during an emergency, or if there is 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 482°F 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 300°F."

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 800°F. 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, and 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, should it fail 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 feet per minute per square foot 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 or 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, (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 482°F 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 482°F 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.

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 outside 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 2000 fpm, 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 2000 fpm, the energy savings may not offset the cost of the evasé.

In a vertical or near-vertical exhaust fan discharge connection to an exhaust duct or shaft, rainwater will run down the inside of the stack into the fan. This water will dissolve material deposited from vehicle exhaust on the inner surface of the stack and become 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 500 fpm. Bird screens should be provided if the exhaust airstream is not continuous (i.e., 24 h a day, 7 days a 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 (1999).

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