Fort McHenry Tunnel Ventilation System

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The problems encountered in designing a satisfactory ventilation system for the Fort McHenry Tunnel in Baltimore are reviewed. The methods for determining the air distribution rates and the air-handling criteria are discussed. The ventilation system designs are discussed as they relate to ventilation building layout (particularly near the historic fort), fan types, airflow, duct design, pressure loss, fire safety, other system features, and the environment that the system will create in the tunnel.

The Fort McHenry Tunnel will carry Interstate 95 under a navigation channel in the northeast branch of the Patapsco River about 4.8 km south of downtown Baltimore. The tunnel, which will be about 2.2 km between portals, will carry four northerly and four southerly lanes of traffic in twin binocular tube sections. When finished, this cut-and-cover and sunken-tube facility will be the longest eight-lane roadway tunnel in the world.

The horizontal and vertical alignment will pass within 413 m of Fort McHenry; it will not interfere with shipping in the channel, and it will meet the I-95 roadways, as shown in Figure 1. Figure 2 shows the tunnel grades, and Figure 3 shows the tunnel tube sections.

Certain design criteria limited the design options available for the ventilation system. To take the least amount of land and select the most direct air duct routing, the design dictated placing the ventilation buildings directly over the tunnels. The west ventilation building near Fort McHenry will have only one fan floor level because of building height restrictions and roadway restraints. Some parts of the box-section cut-and-cover tunnel will form the substructure for the ventilation buildings, as shown in Figure 4. Figure 4 also shows how providing the exhaust and supply systems for each tunnel tube effectively creates the need for four ventilation systems.

Fort McHenry dates from the early Revolutionary War when the first fortifications were constructed to control the entry to Baltimore Harbor. Its chief historic significance dates from the War of 1812, when Francis Scott Key was a prisoner aboard a British man-of-war that bombarded the fort during the night of September 13, 1814. Key's relief at seeing the flag at dawn led to the writing of the poem that became our national anthem. The fort is now a historical landmark of national significance. The closeness of the tunnel alignment to the fort therefore led to a number of important design restrictions.

VENTILATION REQUIREMENTS

Exhaust emissions that contain toxic gases and particulate matter are generated by internal-combustion engines, and these emissions can impair one's health and vision if they are allowed to build up. Ventilation systems are designed for tunnels to prevent these buildups. The piston effect caused by cars passing through short tunnels is sufficient to dilute intolerable emission concentrations, but more positive mechanical means are required for the longer tunnels. The 2.2-km tunnel length posed a considerable design challenge, since it will be the longest eight-lane tunnel in the world.

The problems to be solved in designing a tunnel ventilation system include the following objectives:

1. Determine the supply and exhaust air volumes needed for a safe and comfortable tunnel environment,
2. Establish the ventilation design criteria,
3. Provide the basis for determining the ventilation airflow rates,
4. Describe the ventilation sections,
5. Define the dimensional properties of the air ducts, and
6. Evaluate other general ventilation system features.

Semitransverse and fully transverse ventilation systems were the types that could be considered for this tunnel. In the semitransverse system, a separate duct parallel to the roadway is used to introduce either supply air (outflow) or remove vitiated air (inflow) at intervals along the tunnel roadway. This results in longitudinal airflow in the tunnel either to or from the portals, thus completing the ventilation circuit. The outflow type is the preferred system. However, problems arise with this system in a 2.2-km tunnel because of the excessive amount of air that must travel in the roadway area to escape at the portals. Another disadvantage is discharging the vitiated air at the portals instead of at ventilation buildings located some distance away from the roadways. The same problem with roadway airflow exists for the inflow system, except that the portals are the fresh air sources and contaminant concentrations can build up as the lowest point of the tunnel is reached. Both flow types present serious disadvantages for the Fort McHenry Tunnel.

In the fully transverse system, two individual supply and exhaust ducts that are separate from the road air space provide supply air and exhaust vitiated air along the tunnel length. The system does not cause longitudinal airflow, and air enters and leaves the tunnel at intake and exhaust vents in the ventilation buildings. This system was adopted for the project. Most authorities recommend this type for tunnels more than 1 km in length because it does not induce longitudinal airflows.

VENTILATION CRITERIA

The ventilation criteria called for controlling the concentration of pollutants by diluting the tunnel atmosphere with mechanically introduced ambient outside air. The rate of ventilation should be sufficient to reduce the concentration to an acceptable level and should maintain that level.

The design concentration for pollutants was set at not more than 125 parts per million (ppm) of carbon monoxide (CO) at design conditions. The procedure followed in determining the ventilation rate to satisfy this criterion is found in the 1978 American Society of Heating, Refrigerating, and Airconditioning Engineers (ASHRAE) handbook. This procedure was modified to reflect the U.S. Environmental Protection Agency's (EPA) design traffic emissions.

The design conditions used in determining the ventilation rates were as follows:

1. Design traffic flow: The worst possible condition of traffic was that traveling at 4.46 m/s and at a 1500-vehicles/h/lane traffic flow.
2. Design traffic emission: The amount of CO emitted to the tunnel atmosphere by various vehicles was taken from selected data in the EPA's handbook

on mobile source emissions, except that 1978 vehicle-year rates were used for all 1979 and later vehicles.

3. Design traffic mix: A traffic mix of 86 percent passenger cars, 4 percent gasoline-powered trucks, and 10 percent diesel-powered trucks was selected. The table below shows the traffic projections for 1984, when the tunnel is expected to open, and for 1995, the design year for the tunnel:

Item	Opening Year (1984)	Design Year (1995)
Peak-hour traffic projection (vehicles/h)		
Northbound	5100	5 400
Southbound	4166	4 900
Total	9266	10 300
Directional split (north/south) (%)	55/45	52/48
Vehicles (%)		
Cars	86	87
Trucks		
Gasoline	4	5
Diesel	10	8

4. Profile: Figure 2 shows the tunnel profile and the percent grades in each section.

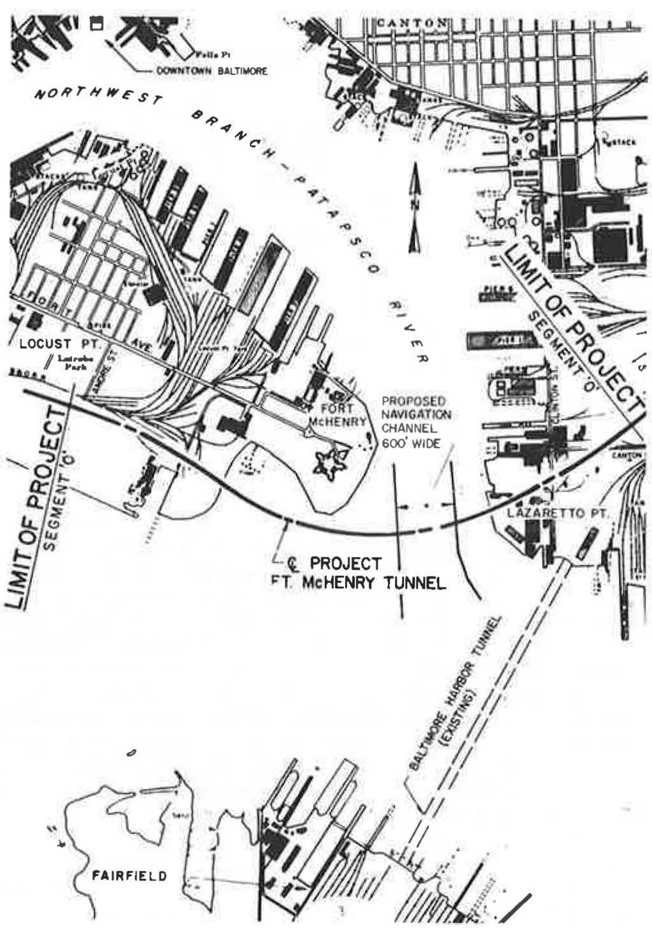
5. Direction of traffic: Each tunnel tube will carry two lanes of one-way traffic, and this direction will not be reversed.

6. Minimum ventilation rate: A ventilation rate of 155 L/s/lane-m was used as the minimum ventilation rate for reasons of safety during fires or other emergencies.

7. Abmient environment: The ambient CO levels (background concentrations) at the wall intakes were considered in the ventilation analyses.

8. Haze and other pollutants: CO concentrations were the basis for determining the ventilation rates. Experience shows that other pollutants are kept within tolerable limits for the predicted traffic mix if the CO concentrations are kept within tolerable limits.

Figure 1. Key plan for Fort McHenry Tunnel.



RECOMMENDED SYSTEM

The tunnel is divided into ventilation sections that are typically estimated to be bounded by the portal at one end and the half-ventilation-volume point at the other (see Figure 5). The exact location of the bulkheads that will establish these dividing points will be determined during the final design on the basis of balancing the section operating horsepower requirements. Each section will have supply and exhaust fans and ventilation controls for independent operation. This division into sections will keep the number of fans and, hence, the ventilation building sizes, electrical components, and controls within reasonable limits. Preliminary calculations indicate the air volume required for each section will not generate excessive velocities in the available duct sizes.

The fully transverse ventilation system for each roadway in the sunken-tube trench tunnel will have separate supply and exhaust ducts, as shown in Figure 6. Supply air will be introduced at the traffic level via peripheral flues from the supply air duct below the roadway slab, and vitiated air will be withdrawn through ceiling ports into the exhaust duct above the suspended ceiling. Both the supply and exhaust ducts will be located above the roadway in the cut-and-cover tunnel sections (see Figure 7).

The size of the supply and exhaust air ducts is a function of tunnel airflow requirements, allowable air duct velocities, internal tunnel geometry, and economic trade-offs between capital construction and operating costs. Table 1 gives the estimated supply and exhaust air volumes developed by the preliminary analysis. The estimated velocities these volumes will produce in the differing tunnel cross sections are given in Table 2.

The estimated required supply air volumes are 1608 and 1546 L/s for northbound and southbound traffic, respectively. The length and the inclina-

Figure 2. Profile at centerline of tunnel construction.

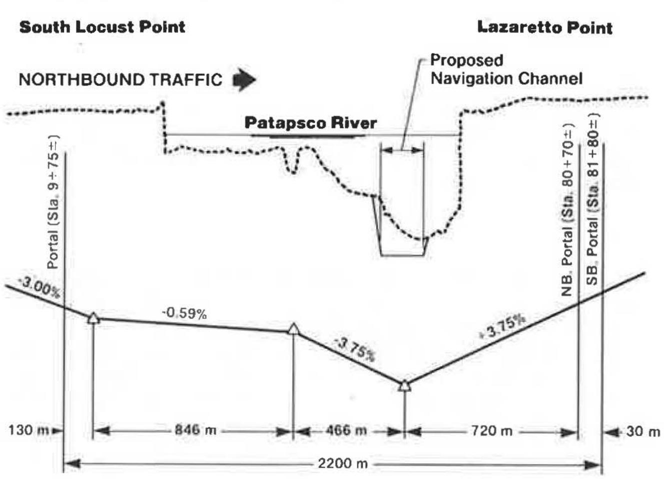


Figure 3. Tube sections.

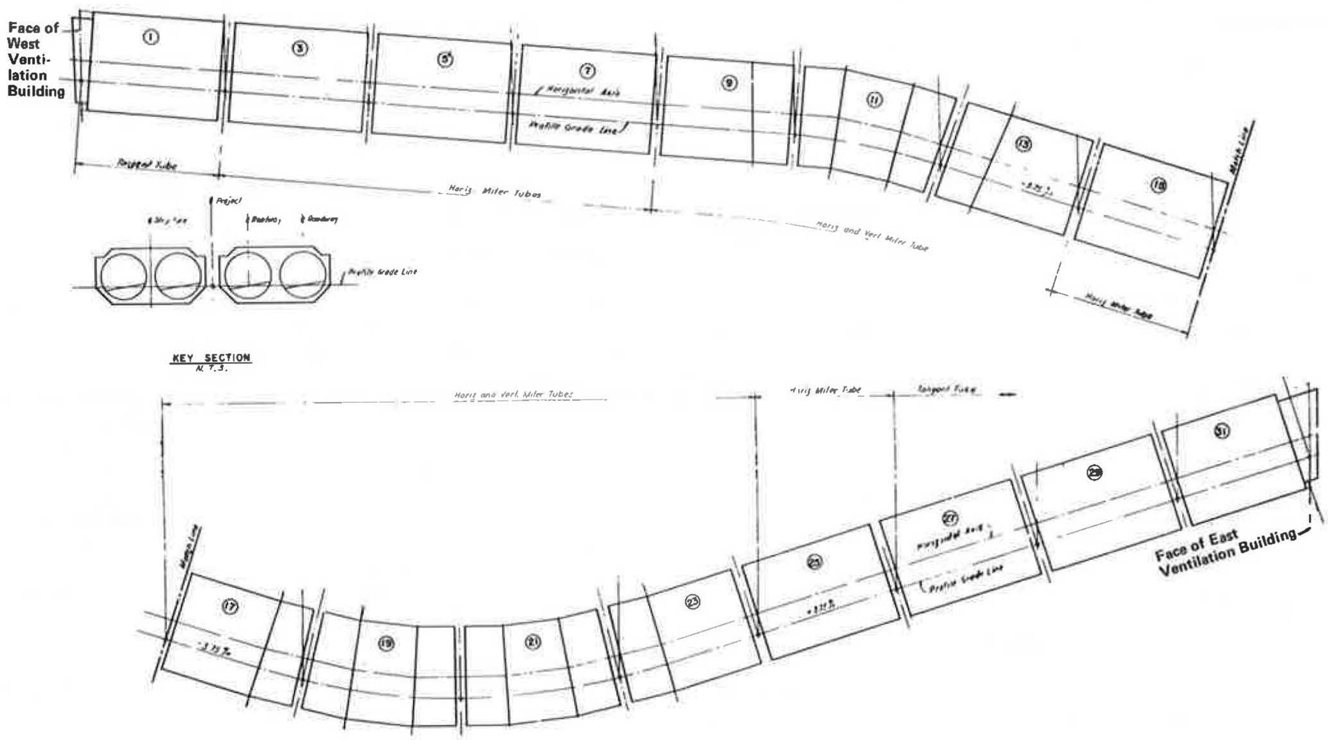
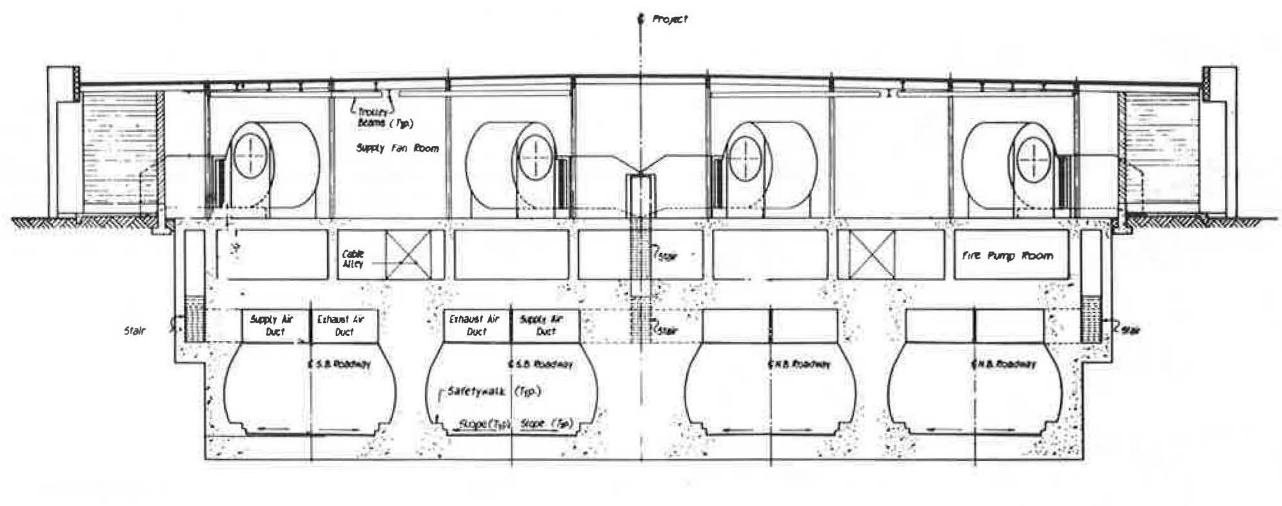


Figure 4. West ventilation building, land section.



tion of the roadway grades, the number of lanes, the traffic composition, and the ambient background CO emissions were considered in deriving these volumes. The exhaust air volumes are assumed to equal the supply air volumes.

FAN TYPES

Both centrifugal and vaneaxial fans were considered for this installation. Centrifugal fans were selected, however, partly for the reasons that follow and partly because the 9.1-m height constraint for the west ventilation building and its effect on the building layout precluded optimizing the best features of the vaneaxial fan.

The most appropriate centrifugal fan for vehicular tunnel use is the double-width double-inlet type with backwardly curved blades. These fans are suitable for parallel operation, have a nonoverloading characteristic, and maintain high efficiency over a wide range of air volume deliveries. These fans can also be operated relatively efficiently at low speed to optimize power consumption and achieve favorable acoustical characteristics. These fans are particularly well suited for exhaust duty because their design is adaptable to handling the high-temperature air produced during a fire if their motors and drivers are located outside the air stream. The motors can be mounted on the floor beside the fan where they can be easily serviced or replaced.

Vaneaxial fans are lightweight, compact, and can be mounted either vertically or horizontally. With a common shaft and only two bearings, misalignment problems in field erection are virtually non-

Figure 5. Typical longitudinal section.

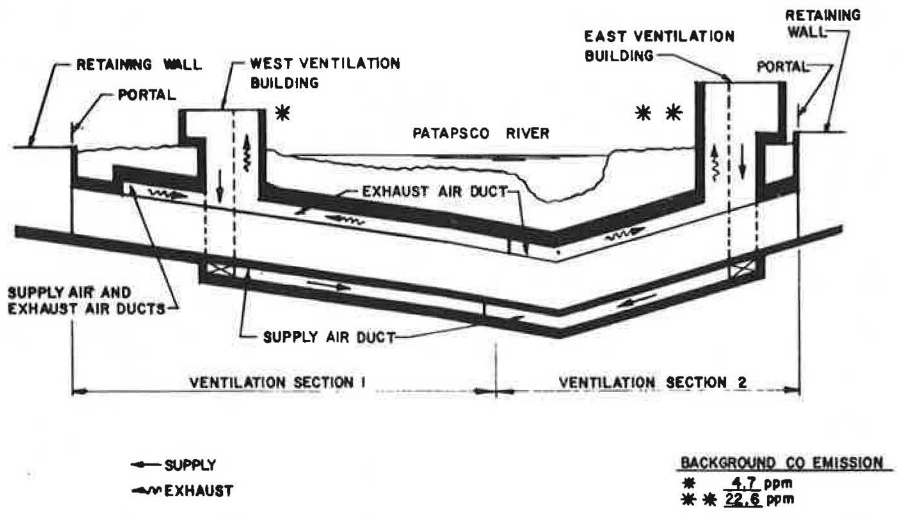


Figure 6. Typical tube cross section.

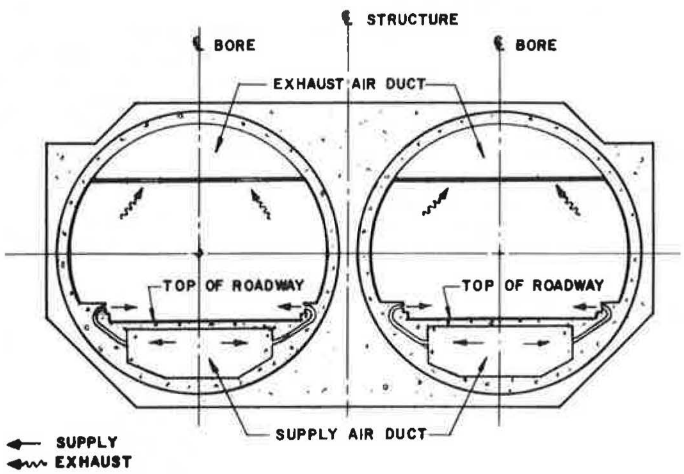
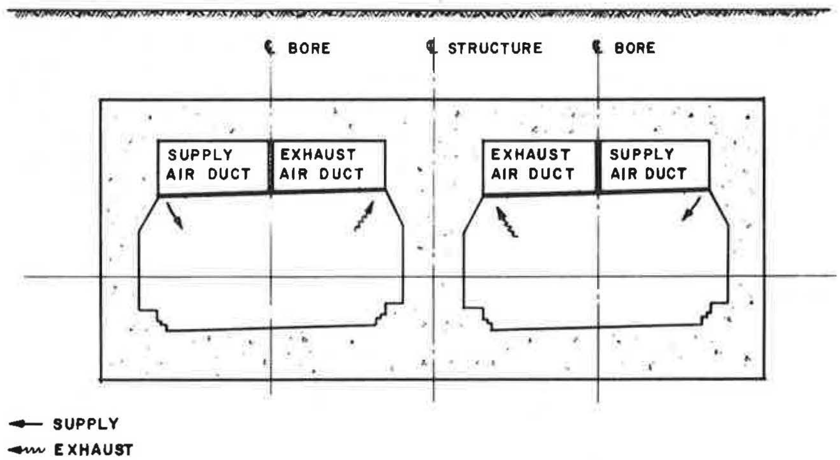


Figure 7. Typical cut-and-cover section.



existent. The acoustical properties are not generally as good as centrifugal fans, but sound attenuators can be readily installed to reduce the sound to acceptable levels. These fans can be reversed electrically, which increases operating flexibility during emergencies, and the axial fan with the motor in the hub can be specified to handle air with a maximum 175°C temperature. Exhaust ventilation service during a tunnel fire, however, usually requires deluge water sprays to protect the motors and the bearings. Even with these sprays, the fans cannot be kept in operation at temperatures as high as those handled by centrifugal fans. Servicing the fan motor is also more of a problem, since the entire unit must be completely removed from its in-duct position.

FAN ARRANGEMENT

Three factors generally govern the selection of the number of fans in each duct system and their operating speeds. The first (and probably the most important) is the practical size of the fan, which considers both cost and size for shipping to the site. The second is providing enough operating capacity steps to meet the varying ventilation demands. The third factor is the system's reserve or standby capacity.

Fan Size

Fans with a nominal wheel diameter of 2.74 m are as large as were considered for shipping to the tunnel site, even though diameters up to 3.66 m have been used in tunnel ventilation. The larger fans are more costly and present serious shipping problems. The 2.74-m-diameter fans can be conveniently shipped on railroad freight cars and trailer trucks. They will satisfactorily handle air volumes up to 189 L/s at the pressures probably required to satisfactorily ventilate the tunnel. This established the upper capacity limit for each fan in each duct system.

Operating Capacity Steps

Operating capacity steps provide the lesser volumes of ventilating air required when lower volumes of traffic are present in the tunnel. In tubes such as the Fort McHenry Tunnel, the very low-level ventilating speeds will be used most of the time.

The number of operating capacity steps in a system is a function of both the number of fans in the duct and the number of speed changes per fan. Fans operating in parallel on the same system, however, should always be run at the same speed, which limits the number of possible air volume changes. Three fans each with two speeds (full and half-speed) will give five capacity steps. Seven steps can be provided with either three fans that have three speeds or four fans that have two speeds, and nine steps will result from an arrangement of three fans with four speeds.

Table 3 gives the number of operating steps and the airflow capacities that will result from each of the four most probable fan arrangements. The table is based on using two, three, or four multiple-speed fans in a three- or four-speed system in a typical Fort McHenry Tunnel ventilation section.

The number of operating hours at each of the possible operating steps will, of course, vary with traffic density. Table 4 gives the number of daily operating hours that were established for each of the four arrangements in Table 3, based on the experience at existing urban tunnels. The table covers a typical supply or exhaust system. Although the actual tunnel air volumes will vary from those shown for a typical section, the table is considered to be representative of all the systems for the Fort McHenry Tunnel.

Table 4 also shows the average ventilation system first-costs, exclusive of the fan first-costs. Because the total number of systems is 16, the costs in the table must be multiplied by 16 to derive the project cost.

Reserve or Standby Capacity

Reserve or standby capacity is the last significant factor in determining fan arrangement. Table 3 shows that a 15 percent drop in delivered air volume will result if one of the three fans operating at high speed is removed from service. Each ventilation section in the tunnel will have two complete systems--one supply and one exhaust--and it is

Table 1. Design ventilation requirements.

Grade (%)	Ventilation Rate (L/s/lane-m)	No. of Lanes per Roadway	Roadway Length (m)	Air Volume (L/s)
Southbound[a]				
-3.75	155	2	755	233
+3.75	248[b]	2	226	112
+3.75	211[c]	2	241	102
-0.59	163	2	846	276
+3.00	198	2	130	51
Northbound[d]				
-3.00	155	2	130	40
-0.59	155	2	846	262
-3.75	155	2	466	144
+3.57	248[b]	2	720	375

[a] Supply or exhaust air volume/roadway = 773 L/s; total southbound supply or exhaust air volume = 1546 L/s.
[b] East ventilation building background emission contributes.
[c] West ventilation building background emission contributes.
[d] Supply or exhaust air volume/roadway = 804 L/s; total northbound supply or exhaust air volume = 1608 L/s.

Table 2. Air duct properties.

Item	Supply Air Duct			Exhaust Air Duct		
	Perimeter (m)	Area (m^2)	Air Velocity (m/s)	Perimeter (m)	Area (m^2)	Air Velocity (m/s)
Ventilation section 1						
Southbound						
Cut-and-cover	11.7	7.43	17.35	11.7	7.43	17.35
Tube section	14.8	12.0	24.6	17.7	11.8	24.9
Northbound						
Cut-and-cover	11.7	7.43	15.35	11.7	7.43	15.35
Tube section	14.8	12.0	25.5	17.7	11.8	25.9
Ventilation section 2						
Southbound tube section	14.8	12.0	28.4	17.7	11.8	28.9
Northbound tube section	14.8	12.0	31.2	17.7	11.8	31.7

highly unlikely that one fan in each system will not be available for service at any one time. A 15 percent capacity loss in one system can therefore be tolerated without seriously affecting tunnel operations or the tunnel air quality. Table 4 also shows that the full ventilating capacity will, on average, be required for less than 1 h/day. Therefore, a three-fan system that provides 100 percent capacity at high speed was selected.

Table 4 also shows the average current power cost for a single tunnel ventilation section, which is based on assumed energy costs, demand charges, operating life, and interest. By using this information and relevant first-cost data, the most economical

Table 3. Fan arrangement operating steps and airflow capacities.

Fan Arrangement and Description	Operating Step	Operating Condition: No. of Fans	Operating Condition: Fan Speed	Air Delivery Capacity (%)
Three fans/duct, three speeds/fan	1	1	Low	16
	2	2	Low	27
	3	3	Low	33
	4	2	Medium	55
	5	3	Medium	67
	6	2	High	85
	7	3	High	100
Four fans/duct, two speeds/fan	1	1	Low	19
	2	2	Low	35
	3	3	Low	44
	4	4	Low	50
	5	2	High	69
	6	3	High	89
	7	4	High	100
Three fans/duct, four speeds/fan	1	1	Low	12
	2	2	Low	20
	3	3	Low	25
	4	2	Intermediate	41
	5	3	Intermediate	50
	6	2	Medium	61
	7	3	Medium	75
	8	2	High	85
	9	3	High	100
Three fans/duct, two speeds/fan	1	1	Low	24
	2	2	Low	41
	3	3	Low	50
	4	2	High	85
	5	3	High	100

Table 4. Comparison of centrifugal fan arrangements under practical operating conditions.

Fan Arrangement and Description	No. of Steps	Fans: No.	Fans: Speed (setting)	Fans: Speed (rpm)	Total L/s to Duct	Total kW	Daily Hours of Operation	Daily kW·h	Present Worth of Power ($000s)	First-Cost ($000s): Motors	First-Cost ($000s): Total
Three fans/duct, three speeds/fan	1	1	Low	121	68	7.5	8				
	2	2	Low		114	15.7	2				
	3	3	Low		142	23.9	5				
	4	2	Medium	243	232	126	4	2575	1568	110	1678
	5	3	Medium		283	191	3				
	6	2	High	364	357	420	2				
	7	3	High		425	650	<1				
Four fans/duct, two speeds/fan	1	1	Low	196	82.5	15.7	8				
	2	2	Low		147	37.3	7				
	3	3	Low		189	60.4	2				
	4	4	Low		213	80.5	2	2920	1650	86	1736
	5	2	High	392	294	302	3				
	6	3	High		378	486	2				
	7	4	High		245	650	<1				
Three fans/duct, four speeds/fan	1	1	Low	91	52	3.1	4				
	2	2	Low		85.5	6.8	4				
	3	3	Low		107	10.5	2				
	4	2	Intermediate	182	173	53	4				
	5	3	Intermediate		213	81.5	2	3023	1690	117	1807
	6	2	Medium	273	260	180	4				
	7	3	Medium		319	276	2				
	8	2	High	364	357	420	2				
	9	3	High		425	650	<1				
Three fans/duct, two speeds/fan	1	1	Low	182	102	25.4	8				
	2	2	Low		173	53	7				
	3	3	Low		213	81.5	3	3820	1863	85	1948
	4	2	High	364	257	420	6				
	5	3	High		425	650	<1				

[a]Does not include fan first-costs.

fan arrangement was determined to be three fans per duct, each having three speeds. The number of fans will therefore be 6/ventilation section, 12/bore, or 48 for the total facility. Each of the two ventilation buildings will house 24 fans. Each exhaust fan will be mounted in a separate chamber with a removable wall or partition between the transmission drive and the fan. This will isolate the motors and drivers from the airstream in an environmentally controlled space and ensure system capability to operate during a tunnel fire.

CONCLUSION

The amount of air required to maintain a safe and comfortable environment in the Fort McHenry tunnel was determined by using the ASHRAE vehicular tunnel ventilation method. The distribution system was also determined by using the same method and resulted in selecting a fully transverse ventilation system comprised of three centrifugal supply fans and three centrifugal exhaust fans for each ventilation section, where each fan has three speeds. This results in a total of 48 fans in the completed facility; the ventilation system will deliver a maximum of 1608 L/s in the northbound and 1546 L/s in the southbound traffic tubes.

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Tunnel-Lighting Engineering for Traffic Safety: Theory Versus Practice

A. KETVIRTIS

The tunnel-lighting design criteria proposed by various authoritative technical societies on a worldwide scale are reviewed. The paper compares the recommended design practices with actual engineering and installation methods used in North America and in other parts of the world. A case study of the Thorold Tunnel is discussed, and the difficulties in designing tunnel lighting based on present methods are reviewed. Suggestions are made for possible practical solutions to meet the driver's needs with minimal energy consumption.

In daytime traffic, motorists passing through a tunnel or a long underpass will experience a visual disturbance caused by the sudden change in luminance levels at the tunnel entrance and in its interior. The degree of difficulty will depend mainly on the suddenness and magnitude of the reduction step in luminance levels. Thus, the problem is related to the ratio of outdoor luminance (L_1) and its level in the tunnel interior (L_2), as well as the speed of travel. Due to the presence of several independent variables that affect a driver's visibility, the question arises of how to determine the luminance levels at the tunnel entrance that would permit safe traffic flow in each specific situation.

National and international organizations, such as the International Commission on Illumination (CIE) (1) and the Permanent International Association of Road Congresses (PIARC) (2), offer practical methods and guides for achieving solutions in tunnel-lighting design. However, due to the varying opinions of individual researchers regarding eye performance under actual dynamic conditions, as well as the different economic factors that exist in various parts of the world, the suggested practices also differ. Furthermore, disagreement regarding the methods of determining the luminance ratios between outdoor (L_1) and tunnel interior (L_2) exists not only between individual engineers but also between technical societies.

DARK ADAPTATION

Eye Limitations to Dark Adaptation

The visual difficulties experienced at the entrance to a tunnel in daytime driving refer to the psychophysical aspects of dark adaptation. The majority of the information input required for driving is obtained in the form of visual data. A sudden change in the prevailing luminance levels may result in total or partial interruption of the flow of visual data, thus seriously affecting contact with the surroundings. In vehicular traffic, such a phenomenon is demonstrated in daytime driving when a vehicle enters a tunnel that has significantly lower luminance in the interior than the exterior.

When the motorist's eyes are presented with an abrupt change in luminance levels, a burst of retinal activity may cause a temporary interruption in the flow of visual information. The detection of objects will be impaired for a varying period of time until adjustment within the system of vision reaches a state of adequate stability. Although theoretically the human eye is capable of accommodating a very wide range of luminance levels (reaching a ratio of 1:10 000 000), a problem is created by the fact that such accommodation involves time. A complete adaptation from the daytime luminance to the starlight level will require about 30-40 min; however, partial adaptation occurs much faster. In the case of conditions at the tunnel entrance, therefore, partial adaptation can only be considered because, in most cases, when driving through a medium-length tunnel, the duration of the process is limited to a fraction of a minute.

Figure 1 (from Mathey) shows the dark-adaptation factor, which represents the average value and the maximum value for normal observers (3). (Note that