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Development of Tunnel Operations and Preventive Maintenance in Quebec

JACQUES ALEPIN

In the Montreal area, 30 000 ft of expressway lanes run through tunnels, two of which are remarkable by their size and design. These tunnels are the Louis-Hippolyte-Lafontaine Tunnel, which runs under the St. Lawrence River, and the Ville-Marie Tunnel, which is situated in the very heart of the City of Montreal. Both of these tunnels are located on Autoroute 20, which forms part of the Trans-Canada Highway. The implementation of these tunnels in Quebec and their development in operations and preventive maintenance (i.e., operations, electromechanical installations, communications, closed-circuit monitoring, and all other work related to operating tunnels) are discussed.

The two most important expressway tunnels in the Province of Québec are located in the Montreal area. These are the Louis-Hippolyte-Lafontaine Tunnel and the Ville-Marie Tunnel. Both are part of the Trans-Canada Highway (Autoroute 20).

The Louis-Hippolyte-Lafontaine Tunnel, which passes under the St. Lawrence River, was the first to be completed. The entire project, including approaches, interchanges, and the tunnel itself, took less than four years to build (July 1963 to March 1967). This is truly an underwater gallery, which measures 1.12 miles in length and has two three-lane tubes. In addition, the central section is made up of seven independent prestressed concrete elements that were prefabricated in dry dock, towed to the site, and then submerged.

The two end sections of the tunnel--one measuring 530 ft on the north shore of the St. Lawrence and the other 1480 ft on the shore of Ile Charron--were both built on site. Two ventilation towers form part of this huge complex. The one located on the north side is used as the operations and monitoring center for the Lafontaine Tunnel.

The Ville-Marie Tunnel was built between 1971 and 1974 and runs in an east-west direction under the very heart of Montreal for a distance of 1.06 miles. There are two main tubes, each with three to five traffic lanes, but the principal feature of this tunnel is its many underground connecting points (the University Street interchange being the most important).

The Ville-Marie Tunnel complex has five ventilation towers that are spaced about 1000-1500 ft apart. One of the towers--tower number 9--which is located at the corner of Busby and Viger Streets, serves as the operations and monitoring center for the tunnel.

In addition, following a government decision to extend the Ville-Marie expressway, another tunnel is currently under construction. This extension, the future Viger Tunnel, was necessary in order to preserve a green space--the Viger Park. This new tunnel section, which will be 1500 ft in length, will have underground ventilation towers in order to comply with City of Montreal town planning requirements. They will rise approximately 16 ft above ground level and will blend in with the environment. The cost of the Viger Tunnel will be $35 million.

TRAFFIC MONITORING

In order to obtain factual statistics on the number of vehicles traveling in each lane of the tunnel, the Ville-Marie Tunnel builders installed capsules that were supposed to provide a vehicle count. It was soon evident, however, that use of such capsules was unsuitable for underground roadways, as the traffic readings were incorrect. The capsules have since been replaced with a magnetic-tune-loop system similar to that used in the Lafontaine Tunnel, which has been reliable up to now.

Because they are located in a highly urban area, the Lafontaine and Ville-Marie Tunnels take care of a great deal of traffic. The Lafontaine Tunnel's summer daily average traffic is 96 000 vehicles. One can readily imagine that there is a high risk of an incident occurring in these tunnels. Thus, the importance of adequate monitoring is warranted.

With closed-circuit television in the control room, traffic controllers can monitor inside the tunnel on a full and constant basis. In fact, the surveillance and control equipment is installed in such a way that when a vehicle enters the tunnel, the controller can follow its progress without ever losing sight of it until it leaves the tunnel.

By using this type of monitoring, it is possible to detect the slightest incident occurring inside the tunnel and to correct it without delay. As soon as an incident is identified, whether it be a fire, an accident, or a breakdown, the controller uses the overhead traffic lights to direct the flow of traffic. For instance, the red light is switched on above the lane where the incident has occurred and its traffic is diverted to adjacent lanes by means of flashing amber lights.

Experience has shown that in such circumstances, Lafontaine Tunnel users almost always obey traffic light signals, whereas motorists who use the Ville-Marie Tunnel more often wait to see what has happened before reacting and moving over to adjacent lanes. Therefore, there is reason to suppose that the Ville-Marie Tunnel alignment changes the motorist's field of vision in such a way that, under certain angles, the traffic light on the driver's right is in his or her direct line of vision, thereby resulting in a slow reaction time when an incident occurs.

COMMUNICATIONS

Now, let us turn back to the controller. Once the flow of traffic is back to normal by means of the traffic lights, the controller must take another action, depending on the type of incident. In the case of a stalled vehicle, he or she calls the towing services. I should point out at this time that for all the Montreal area expressways, including the tunnels, the Ministère des Transports has turned over the job of providing breakdown services to private firms. It is up to the controller to give all necessary information to the towing services, such as the exact location of the breakdown and the type of vehicle. Statistics show that it takes an average of 12 min to respond in the case of both tunnels. Moreover, during rush hours a tow truck is on standby at the entrance to the Lafontaine Tunnel. In fact, during these crucial moments, the tow truck's response time is approximately 5 min.

If an accident occurs, the controller must notify the police authorities and, if necessary, the ambulance services. If there is a fire, the controller sets in motion fire-fighting arrangements made with the fire department of the City of Montreal. Until the arrival of the firemen on the scene, tunnel employees operate such fire-fighting equipment as fire extinguishers and fire hoses located in built-in cabinets placed some 250-300 ft apart along the tunnel walls. The fire fighters can reach the scene of the fire by driving through the tunnel against the flow of traffic when assisted by police officers.

Another of the controller's duties is reversing the ventilation system in the affected section and operate it so that the smoke and harmful fumes can escape without causing discomfort to motorists and without fanning the fire. Fortunately, there have been no major fires in the Lafontaine and Ville-Marie Tunnels since they have opened to traffic. Only a few cars have caught fire in the Lafontaine Tunnel.

An act, which has been in force since 1974 and prohibits the transportation of dangerous commodities (such as flammable and nonflammable compressed gas, explosives, and oxidizing, radioactive, and corrosive materials) through the tunnels at all times, has greatly reduced the possibility of major fires occurring in the two tunnels. The Ministère des Transport's highway patrols exercise tight control in order to prevent, as much as possible, the transportation of dangerous commodities. Since 1975, they have handed out more than 1100 violation tickets to truckers who carried such cargo through the two tunnels.

Without proper telephone communications with the fire and police departments as well as with breakdown services, the controllers would be unable to cope with the various situations without delay. A telephone service is also available to motorists in trouble in the tunnel. Telephones that provide direct contact with the control center are spaced between 150 and 300 ft apart.

At the Lafontaine Tunnel, antennas provide radio communications between the control room and maintenance vehicles. Due to the different geometry of the lanes in the Ville-Marie Tunnel, it was necessary to install a radian coaxial cable to provide radio contact, without cut-offs, between the control center and maintenance vehicles. This is a community cable network used mainly by the various police and fire departments. When motorists must be evacuated through emergency hallways, the controller can give instructions through a loudspeaker system.

MAINTENANCE

Cleaning the tunnel walls is one of the principal maintenance activities. The department has a brush truck specially designed to do the job, as well as two rinse trucks. The work is done at night, as is most other maintenance work. The tunnels are washed periodically.

Top priority is given to maintaining the lighting system, which is of prime importance inside a tunnel. It is therefore necessary to replace fluorescent lamps at the tunnel entrance about every two years, since this is their approximate effective life span. A truck equipped with a hydraulic platform is used to change the lamps. Relamping inside the tunnel is done every three years, except in the case of the Ville-Marie Tunnel, where lamps were only changed in 1979, five years after its opening. The method of a periodical complete lamp change is preferred for cost reasons. The difference in the frequency of this operation in the two tunnels is due to the higher density of traffic in the Lafontaine Tunnel and, as a result, the fluorescent lamp protective coverings get dirty much more quickly and cause reduced visibility.

With regard to the pavement in both tunnels, it requires about the same maintenance as any surface expressway. The water drainage system is checked and maintained regularly. Catch basins are inspected every three months. In the Ville-Marie Tunnel, scourers are used to clean the drain pipes in the fall.

The water distribution line and the gutter expansion joints are heated by electric cables. Plastic-covered nonflexible copper-sheathed cables are used in the Lafontaine Tunnel, whereas neoprene-sheathed bytil-rubber heating cables are installed in the Ville-Marie Tunnel. These proved to be less resistant than expected and, in some cases, were replaced with the same type used in the Lafontaine Tunnel.

Preventive maintenance is possible with the cardex system set up to record inspections made on the various pieces of equipment in both tunnels. Telecontrolling, telemetering, and telesurveillance of mechanical and electrical parts of the complex are carried out by means of a computer-operated system installed in the Ville-Marie Tunnel. Therefore, it is quick and easy to detect defects or faults in a system, as any abnormality found by the computer immediately appears on a cathodic screen and its principal coordinates are transmitted by printer. A data sheet drawn up by the controller is then forwarded to the person in charge of maintenance. In both tunnels, maintenance of sophisticated equipment, such as motor generator sets, closed-circuit televisions, elevators, the 12-kV electric substations, pumps, ventilation motors, control panels, noninterruption units, and the computer, is done with the help of private firms.

Maintenance of the Ville-Marie and Lafontaine Tunnels is not without its problems because of the numerous mechanical and electrical installations and also on account of the severity of the weather. Some of the problems encountered are rusting of electric conduits, short-circuiting in the alarm wiring, corrosion of fans, water infiltration, and machines jammed by dirt.

Other problems are design related. In the Lafontaine Tunnel, space for easy access to the fans by work crews was forgotten, thereby making it difficult for the crews to handle spare parts when making repairs.

And, of course, there are the more complex problems, such as the lack of follow-up service by sophisticated equipment suppliers and sometimes difficulty in obtaining needed repair parts. One such problem was with regard to the wiring and electric conduits, which were exposed to severe cold in some places. It was decided to replace them with polyvinyl chloride (PVC) conduits and connections, which are more resistant to dampness than galvanized steel. Weatherproof wiring is also used.

VENTILATION SYSTEM

Due to the different configurations of the tunnels, their ventilation systems also differ. For the Lafontaine Tunnel, there are 16 vertical fans and, in 13 years, only one has needed reconditioning. Moreover, none of the 16 fans has suffered significant rust or dirt deterioration, which is undoubtedly due to the fact that the motor and dynamic brake are protected by a self-cooling casing. On the other hand, lack of proper access to the air shafts has caused problems in the handling of spare parts. The installation of doors has partly solved the problem, but it is still difficult to handle parts in eight exhaust fans when breakdowns occur because they are located above the roadways.

Sixty-three fans, which are located in five towers, make up the Ville-Marie Tunnel ventilation system because of the special geometry of the traffic lanes. Handling spare parts is also extremely difficult for 18 of the 63 fans. However, with a little imagination, a solution to part of the problem of lack of access to the fans was found. Instead of using a mechanical winch to make fan repairs, an I-beam with a manually operated trolley was installed, which requires much less maintenance and is cheaper to purchase.

I should also mention that the fan air louvers are often jammed--the victims of rust and dirt--because their opening and closing hardware is not salt-air proof, which is the source of the problem. However, even though the air louvers function automatically and two employees work full time on preventive maintenance, four or five fans are frequently out of order, which is caused by the air louvers. Moreover, since the motors in the Ville-Marie Tunnel are not protected with metallic casings, they are more easily exposed to corrosion, particularly the manually operated brakes. In the long run, it also happens quite often that the propeller blades catch in the ventilator frames. Since 1974, six have had to be replaced. To solve only the air-louver problem would cost approximately $600 000.

Based on experience with the Lafontaine and Ville-Marie Tunnels, suppliers of fans for the Viger Tunnel, which is now under construction, have been given stricter specifications. In the future, the opening and closing hardware for air louvers must be mounted on ball bearings. In addition, all parts of this hardware must be metallized in plant for protection against salt air. As for the ventilator motors and emergency brakes, these must have a metallic casing before being equipped with their own aeration system. In the Viger Tunnel, access to all fans is planned, thereby easing the handling of various spare parts.

Both the Lafontaine and the Ville-Marie Tunnels have a carbon monoxide monitoring system to check the quality of the air. A Hopcalite analyzer was first installed in the Lafontaine Tunnel. However, it required extensive maintenance and proved difficult to calibrate. Furthermore, the pumps used for air sampling, which were placed inside the cubicles, had a tendency to overheat; it was therefore necessary to place them outside the cubicles. Here, too, follow-up service was more or less satisfactory and spare parts were difficult to come by. Therefore, considering the many problems encountered, this carbon monoxide monitoring system was replaced a few years ago with an infrared system similar to the one in use in the Ville-Marie Tunnel. Calibration of this type of analyzer is simpler and readings are more accurate. Furthermore, its maintenance is done by department personnel.

POWER SUPPLY

Hydro-Québec provides the electricity that is essential, needless to say, for the efficient operation of all installations in both tunnels. But for obvious reasons, another source of power had to be available in case of a breakdown in the Hydro-Québec system. This is why a static inverter was installed when the Lafontaine Tunnel was built. This was supposed to supply essential services to the tunnel until the motor generator sets started and absorbed the load. However, the static inverter, which was one of the first of its kind, needed extensive repair work and had one major defect--it broke down at the same time as the Hydro-Québec power failure. It was scrapped in 1969 and never replaced. To compensate for the lack of a static inverter, signs were put up at the entrances to the Lafontaine Tunnel urging motorists to turn on their headlights. According to statistics, 40 percent of the tunnel users do turn them on. The motor generator sets are also turned on during violent storms, ready to take over in case of a power failure. The authorities are now seriously thinking about installing proper inverters to cope with this situation.

The Ville-Marie Tunnel was built at a later date, so it has the advantage of being equipped with a different system for the provision of emergency current. In fact, noninterruption units are installed in each ventilation tower, which provide one-sixth of normal lighting during a power failure and feed the control systems essential for efficient tunnel operation during the lapse of time it takes for the motor generator sets to start functioning, which is approximately 3 min. The noninterruption units are equipped with an AC-DC rectifier, a storage battery, a DC motor, and an alternator. This system has proved most reliable. However, it does require constant maintenance by both the manufacturer and maintenance personnel.

Also, fire broke out in the storage battery room when the noninterruption units were first put into operation. Battery overloading, together with an overflow of acid (rendering the cases current conductors), were the cause of the fire. To solve this problem, hydrocaps had to be fitted to the batteries to condense the acid fumes. Preventive maintenance is done on all batteries; for instance, the water level is checked regularly. The same type of noninterruption units will be installed in the Viger Tunnel.

EMERGENCY EQUIPMENT

In the Ville-Marie Tunnel, there have been many problems with the opening and closing hardware on the doors leading to emergency hallways. Made of conventional steel, these parts were not sturdy enough, got rusty, and jammed easily. They are gradually being replaced with hardware made of stainless steel, like the doors themselves.

Both tunnels are equipped with fire hose cabinets. In the Lafontaine Tunnel, these are large and easy to reach from the emergency hallways, rendering their inspection and maintenance simple enough. On the other hand, the fire-fighting equipment cabinets in the Ville-Marie Tunnel are small, and maintenance personnel have to use a roadway to do the maintenance work, which means closing one traffic lane.

Moreover, fire hoses frequently burned because they were placed too close to heaters. It was decided to roll the hoses instead of suspending them, thereby moving them away from the heaters. And, finally, neoprene-lined hoses, known for their high resistance to cold, were installed in both tunnels.

CONCLUSION

Tunnel designers should bear in mind both tunnel operation and maintenance. In order to minimize the problems and costs related to monitoring and maintenance of future tunnel sections, designers should, and must, consult those in charge of these two essential operations and profit from their past experience. A more judicious choice of lane geometry, materials, and equipment would certainly result from such consultation. The future tunnel section will, therefore, be of optimum design from a structural, mechanical, and functional point of view.

Keeping this objective in mind, the Québec Ministère des Transports has taken into account specific problems encountered in the operation and maintenance of the Ville-Marie and Louis-Hippolyte-Lafontaine Tunnels. The new Ville-Marie expressway tunnel--the Viger Tunnel--will therefore show significant improvements over the other two tunnels.

As a matter of fact, rendering the task of those in charge of operations and maintenance easier should be the main outcome of recommendations made to the consulting engineers working on the tunnel design, while at the same time ensuring greater safety for motorists.

Variable Pitch Axial Flow Fans for Tunnel Ventilation: A Comparison with Centrifugal Fans

HANS DIETER BAESEL

Variable pitch axial flow fans for application in vehicular tunnel ventilating systems are described. The fan design is of German origin and is considered to represent the state of the art, matured over more than two decades of operating experience. Its use for tunnel ventilating systems in the United States appears to be justifiable. The design and performance are described. Three major areas—energy conservation, space requirements, and number of pieces of equipment—provide the largest savings potential and make this fan design most attractive.

The ever-increasing cost of energy is influencing our personal lives as well as our ability to be competitive in a world market. In that regard, the demand for energy conservation has become not only a political factor, but it is also beginning to play a significant role in today's capital-investment decisions, in that operating costs frequently equal or exceed the cost of the initial capital investment. As engineers, therefore, we are obliged to use all available technology or develop new means to reduce or optimize the use of energy to balance and control its impact on the economy.

The purpose of this paper is threefold:

1. To identify major factors that make axial flow fans the best economic choice for capital investment decisions (i.e., reduction in number of operating equipment and reduction in space requirements);
2. To demonstrate that the variable pitch axial flow fans (VPAFFs) used for continuous flow control will significantly reduce total power consumption, which will result in operating cost savings; and
3. To briefly discuss the VPAFF's reliability, noise emission, maintenance, and general vulnerability to tunnel fires.

This paper will not discuss the theory behind fan laws. It will state theory where necessary and use resulting design criteria as required to demonstrate points and make comparisons.

AXIAL FLOW FANS--THE BEST ECONOMIC CHOICE

Reduction in Number of Operating Equipment to Satisfy Ventilation Requirements

A brief explanation of centrifugal and axial fans is given below:

1. Centrifugal fans: A centrifugal fan is a fan whose inlet air enters the fan parallel to the axis of impeller rotation, is turned, and then leaves the fan perpendicular to the axis of rotation. Centrifugal fans are best suited for low-volume flow, high-pressure application. Their use for higher volume flows is accomplished by using the double-width double-inlet (DWDI) design, where two centrifugal fans essentially operate in parallel.
2. Axial fans: An axial fan is a fan where the air enters the fan parallel to the axis of impeller or rotor rotation and leaves the fan with the air still parallel to the axis of impeller rotation. Axial flow fans are best suited for high-volume flow, low-pressure application. Two or more impellers in series are used to extend the axial flow fans use to higher pressure ranges.

Figure 1 shows a simplified method to determine what type of fan or how many fans must be used to meet a given set of conditions. Three variables (volume flow, adiabatic head, and fan speed) characterize the fan's specific speed and indicate the preferred fan type (axial or centrifugal).

To help explain this concept, the following example is given. The total volume flow for a tunnel ventilation section may be 900 000 actual cubic ft/min (ACFM) at 2-in watergauge (w.g.). In selecting DWDI centrifugal fans, it can be recognized that at least three fans, operating at 300 revolutions/min (rpm) or below, should be used to meet volume flow.

When considering axial flow fans, it can be seen that one or two fans operating at 350-600 rpm or above can be used. Considering the example, the following observations can be made:

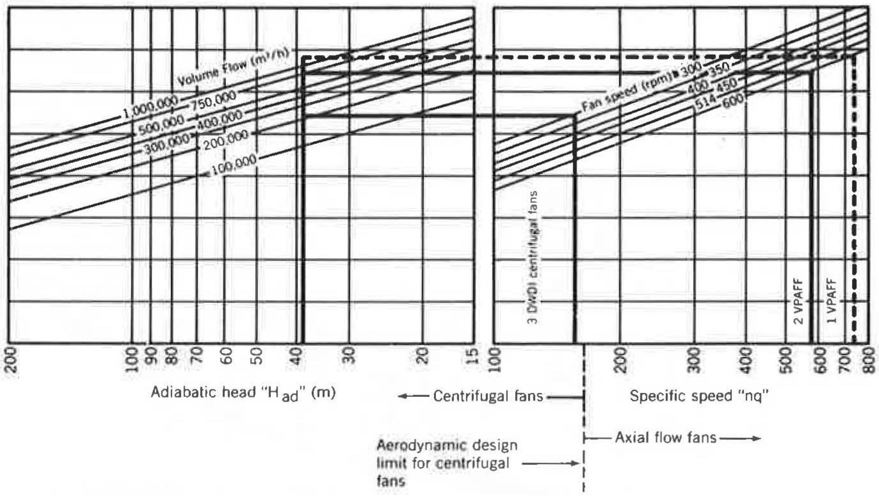
1. Fewer fans are required to move the ventilation air volume flow when using axial flow fans;
2. The higher operating speed of axial flow fans usually permits the use of directly coupled drive motors;
3. Equivalent to the number of fans, fewer drive motors are required;
4. Less motor starting and auxiliary electrical equipment are required;
5. Fewer dampers and damper drives are needed;
6. Fan or motor controls will be simplified;
7. Fewer foundations are required; and
8. The ductwork requirements will be reduced.

Although not quantified in this paper, the items listed above will reduce the overall equipment costs, particularly installation costs.

Reduction in Space Requirements (Reduction of Fan Building Costs)

The costs of the ventilation fan building represent a substantial portion of the total tunnel costs. To keep the fan building costs at their lowest, it is desirable to minimize its physical size. The size of the building, however, is in most cases primarily affected by the number of fans to be installed and their dimensions. With this in mind, the objectives

Figure 1. Fan type selection diagram.



$$nq = n \times \frac{V^{1/2}}{H_{ad}^{3/4}} \qquad (1)$$

nq = Specific Speed
n = Selected fan speed (rpm)
V = Fan volume flow [m^3/s]
H_{ad} = Adiabatic head $\frac{\Delta P}{\delta}$ [m]
ΔP = Total pressure increase [kp/m^2]
δ = Gas density [kp/m^3]

Example:
V = 900,000 [CFM] = 1,529,000 [m^3/h]
ΔP = [2 inches wg] = 50.8 [kp/m^2]
δ = 0.081 lbs/ft³ = 1.293 [kp/m^3]
H_{ad} = = 39.3 m]

for the engineer can be defined as (a) reducing the number of fans necessary for the ventilation system and (b) minimizing the physical dimensions of the fans.

In comparing axial flow fans with centrifugal fans, it has been established that the use of axial flow fans will permit selection of fewer fans for a specific ventilation system. With reference to the above example, one or two axial flow fans are needed compared with three centrifugal fans. With this finding, the first objective of reducing the number of fans is met. (It may be of interest to note that all highway tunnels in Austria are equipped with one fresh air supply fan and one or two exhaust air fans, all of which are of the variable pitch axial flow design.)

Regarding the physical size difference between centrifugal and axial flow fans, the following simplified explanation may provide a better understanding. Comparing a single-width single-inlet (SWSI) centrifugal fan with a single-rotor axial flow fan designed for the same conditions (volume flow and pressure) and the assumption that the flow velocity approaching the centrifugal fan rotor is essentially equal to that approaching the axial flow fan rotor, we can conclude that the total inlet area of the centrifugal fan rotor must be equal to the ring area between the rotor tip and the rotor hub diameter of the axial flow fan.

Because low-pressure axial flow fans need especially small rotor hub diameters, the increase in rotor tip diameter is small to compensate for the lost rotor hub area. Therefore, it will be found that the rotor tip diameter of an axial flow fan will almost fit into the centrifugal rotor inlet dimensions.

Ignoring the influence of rotor blade shape, number of blades, and blade arrangement in a centrifugal fan rotor, it can be stated that the pressure created by the centrifugal fan rotor is proportional to its tip speed. The tip speed depends on rotor outer diameter and rotor speed, whereby the diameter has a reverse proportional relation to the speed.

Since the inlet diameter is set because of volume flow and maximum flow velocity and the outer diameter must be larger than the inlet diameter, a maximum speed will result. We now have to consider that the centrifugal fan rotor is placed in a fan housing that has a spiral-shaped silhouette. This housing acts as a collecting device for the volume flow exiting the fan rotor. Although the housing depth parallel to the rotor axis can be maximized, the housing width and height perpendicular to the rotor axis will still be 80-100 percent larger than the rotor outer diameter. In comparison with the axial flow fan, the centrifugal fan is larger by a factor of 1.8-2.0.

One method of reducing the fan size is to use DWDI centrifugal fans, where only 50 percent of the volume flow approaches each rotor inlet. The inlet area can, therefore, be reduced by 50 percent; however, the inlet diameter of the rotor and its housing will only change by 2, or a factor of 1.414.

Again, by using the example where we identified three DWDI centrifugal fans compared with two axial flow fans, each centrifugal fan will supply only two-thirds of the volume flow each axial flow fan has to move. Consequently, the centrifugal fan inlet area can be reduced by a factor of 0.67, which will reduce the inlet diameter or the housing dimensions by a factor of only 1.23.

Combining the two size-reducing factors by calculating the product, the total factor is 1.74. This result, when compared with the original size difference between axial flow fans and centrifugal fans (factor 1.8-2.0), will lead to the conclusion that each individual centrifugal fan will still be larger than each individual axial flow fan. With this result, the second objective of minimizing the physical dimension of the fans is met.

VPAFFs REDUCE OPERATING COSTS

For the purpose of proving that the use of VPAFFs instead of centrifugal fans will reduce operating costs, it is essential to first discuss the typical performance characteristics of both fan designs in relation to the ventilation system.

Figure 2. Typical performance field of VPAFF.

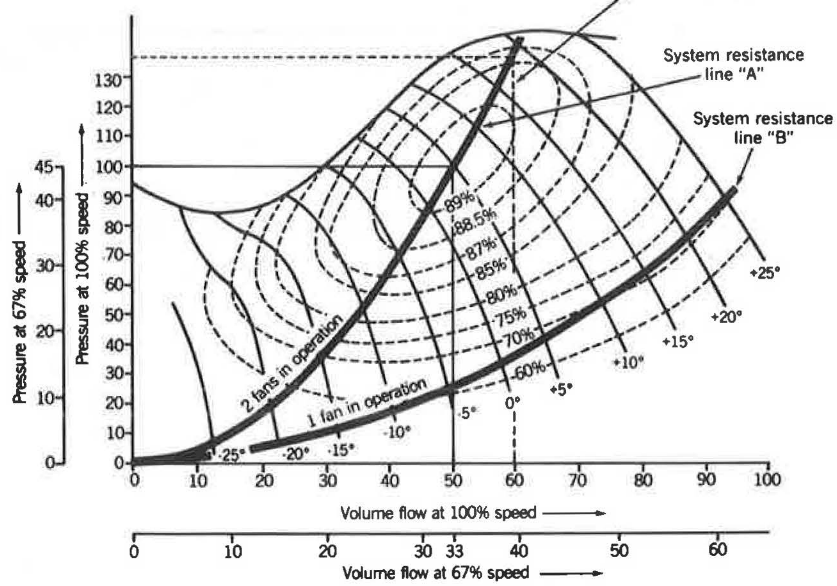
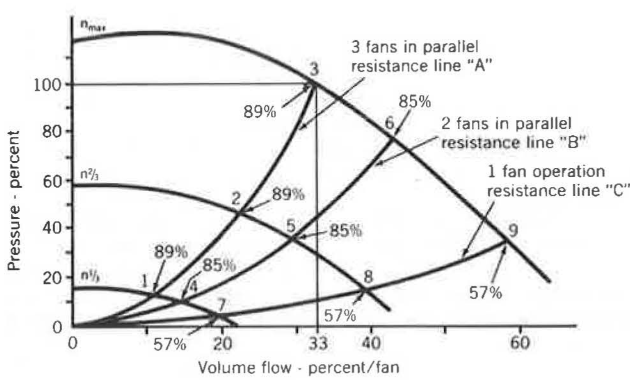


Figure 3. Typical performance field for three-speed radial fan.



VPAFF Performance Characteristics

Figure 2 shows a typical performance field of a VPAFF in an arrangement where two fans operate in parallel. Tunnel ventilation system resistance line A is representative of two fans operating in parallel; each provides 50 percent of the total volume flow. System resistance line B is applicable when one fan is operating. From the performance field, the following observations can be made:

1. Areas of constant efficiency have their maximum extension essentially parallel to the tunnel resistance line, which permits changes in operating conditions over a wide range with high efficiencies.
2. Although each fan is designed to meet 50 percent of the total system volume flow at highest efficiency (resistance line A), 20 percent excess capacity is available.
3. One fan operating alone (resistance line B) can provide 85-100 percent of total volume flow, provided the motor (or motors) is properly sized for the larger volume flow and the reduced fan efficiency.
4. Any volume flow required by the tunnel ventilation system can be met directly by means of rotor blade angle adjustment (intersection points of fan curves for any blade setting with the tunnel resistance line).
5. To increase the extension of high fan efficiencies, and also to maintain high drive motor efficiencies, a second speed, which is normally 67 percent of full speed, is used. (Typically, most ventilation systems equipped with VPAFFs operate with two speed motors or two motors in tandem.)

Centrifugal Fan Performance Characteristics

Figure 3 shows the performance curves of a three-speed centrifugal fan operating in parallel in a three-fan arrangement. Once the maximum 100 percent fan speed (fan design speed) is determined, the two additional fan speeds will normally be selected at 67 and 33 percent of the maximum speed. These conditions are normally met by selecting a single-speed motor for 100 percent fan speed and one two-speed motor for 67 and 33 percent fan speed.

Superimposed on the diagram in Figure 3 are three resistance lines:

1. Tunnel resistance line A is representative for three fans operating in parallel, each providing 33 percent of total volume flow;
2. Tunnel resistance line B is applicable when two of three fans operate in parallel (one fan being shutdown); and
3. Tunnel resistance line C applies when one of three fans operate (two fans being shutdown).

Referring to Figure 3, the following observations can be made:

1. There are nine discrete operating points that can be met (intersection points between the three resistance lines and the three fan speeds) by varying the number of fans in operation and fan speeds;
2. Operating points 1, 2, and 3 are met with maximum fan efficiency;
3. Operating points 4, 5, and 6 are met with a fan efficiency approximately 10 points below maximum;
4. Operating points 7, 8, and 9 are met with an efficiency approximately 25 points below maximum; and
5. In the event of a single fan failure, the

Figure 4. Power savings.

Basis for diagram

$N^* = \frac{V^* \times \Delta P^*}{102 \times \eta}$

V^* = Volume flow %

ΔP^* = Total pressure increase %

η = Fan efficiency

N^* = Power consumption

Actual use of diagram

At $N^* = .011$

$kW = (.011)(900{,}000 \frac{ft^3}{min})(2 \text{ inch WG})$

$(25.4 \frac{mm}{inch})(\frac{1 m^3}{35.31 ft^3})(\frac{1 min}{60 sec}) =$

$= 237$ kW

At $N^* = .002$

$kW = (.002)(900{,}000)(2)(25.4)$

$(\frac{1}{35.31})(\frac{1}{60}) = 43$ kW

Operating point 1

Power savings 59 [kW]

Power cost savings

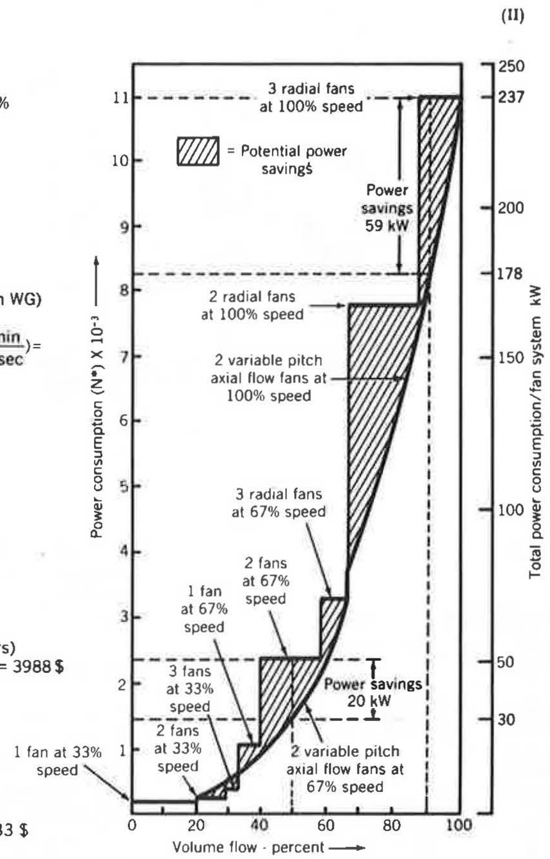
59 x 2 (fan systems) x 1690 (hours) = 199540 [kWh] x .02 [$/kWh] = 3988 $

Operating point 2

Power savings 20 [kW]

Power cost savings

20 x 2 x 3666 (hours) = 146640 [kWh] x .02 [$/kWh] = 2933 $



remaining two fans operating at 100 percent speed will produce approximately 85 percent of the total volume flow.

With the above description, the basis is established to compare the two systems with regard to their total power consumptions, i.e., three centrifugal fans with three speeds versus two VPAFFs with two speeds.

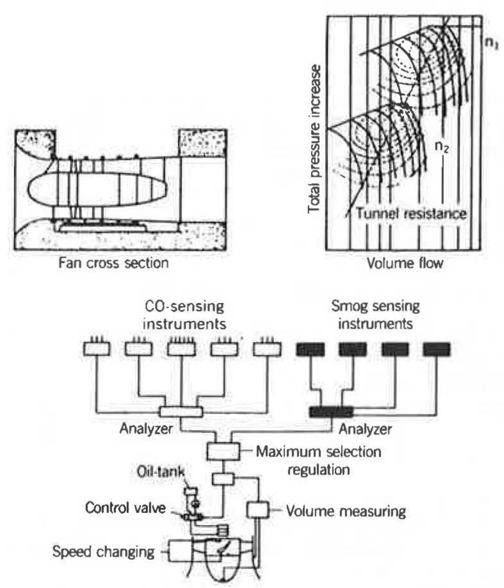
Power Consumption Savings

By using Figures 2 and 3, the total power consumption for each fan system can be calculated. Instead of calculating with actual numbers for volumes and pressures, the calculations were conducted on a percentage basis by using the numbers in Figures 2 and 3. The results are shown in Figure 4.

By using this approach, Figure 4 represents a general tool to conduct power consumption comparisons of the systems; the equations stated in Figure 4 are also important in doing the comparison. The following explanations may be helpful in providing a better understanding of the figure:

1. The diagram shows the difference between a step-control and a continuous-control system (see also Figure 5, which is a schematic of a typical control system for continuous control),
2. The vertical difference between the curve for axial flow fans and the various steps for centrifugal fans for any given volume flow represent the difference in power consumed by the two systems, and
3. The power difference multiplied with the operating hours spent at the various load points and subsequently multiplied with the cost per kilowatt

Figure 5. Schematic of fan and tunnel ventilation control system.



hour results in the operating cost savings that can be realized.

To show an order of magnitude for such operating cost savings, the example previously used in this paper was again used to satisfy the equations stated

Figure 6. Cross section of axial flow fan.

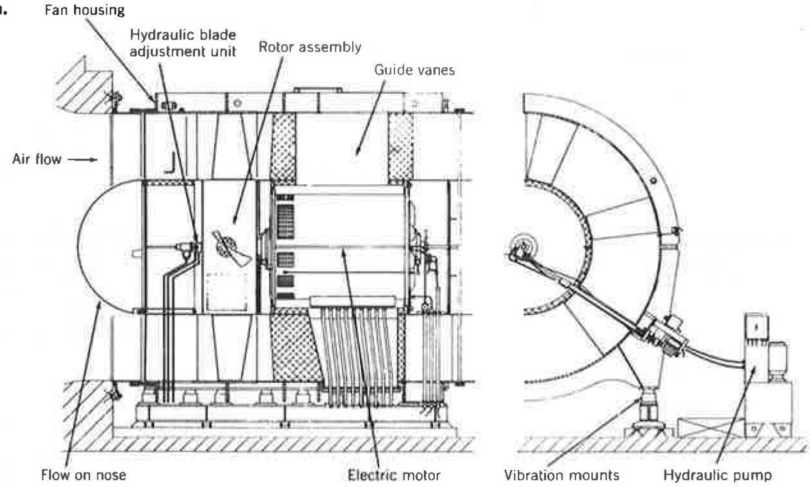
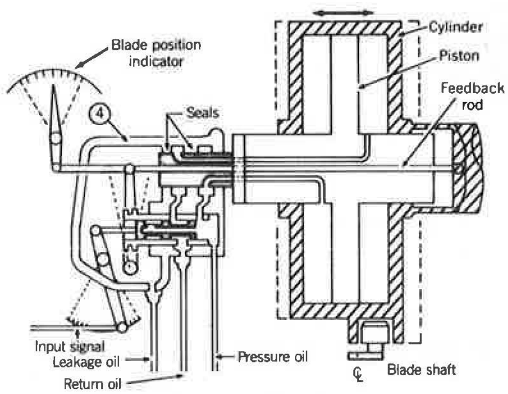


Figure 7. Blade-adjustment mechanism.



in Figure 4. Because the conditions (volume and pressure) meet closely those of a tunnel in a western state that is currently under study, two operating points anticipated in this study were used to compute total operating hours per year.

To identify the overall total for the entire tunnel project, it must be understood that three ventilation sections that consist of six fan systems, as described in the example, are required:

1. Operating point 1: volume flow = 85-100 percent (90 percent) and annual operating hours for a six-fan system = 1690 h; and
2. Operating point 2: volume flow = 39-59 percent (50 percent) and annual operating hours for a six-fan system = 3660 h.

Considering $0.02/kW•h, the annual operating cost savings by using VPAFFs amounts to $6920, considering two possible operating points only. Because two-fan systems in the example serve one tunnel tube ventilation section, it must be recognized that the above operating hours represent only 20 percent of the total annual operating hours of three tunnel tubes.

DESIGN FEATURES

After having discussed aerodynamic and performance comparative characteristics of axial and centrifugal fans and the resulting economic differences in both equipment and operating costs, it is appropriate to address design features as they relate to reliability, maintenance, noise, and, most controversial, vulnerability to fire or high temperatures.

Reliability and Availability

Operating records of centrifugal fans in the United States and VPAFFs in Europe show availabilities, on average, in excess of 99.9 percent. To prefer the one design over the other based on availability is, therefore, not practical. It is also of theoretical value only to state that the probability of a single fan failure increases with the number of operating fans. The probability of a single fan failure when using centrifugal fans is, therefore, theoretically higher than experiencing a single fan failure when using axial flow fans, due to the fact that more centrifugal fans are needed for a ventilation system.

For practical purposes, considering that the average availability per fan is less than 100 percent, a single fan failure is probable and will occur. Considering, however, that two of three centrifugals fans or one of two axial flow fans are sufficient to satisfy tunnel ventilation requirements, the reliability of the entire ventilation system is maintained at an extraordinary high level.

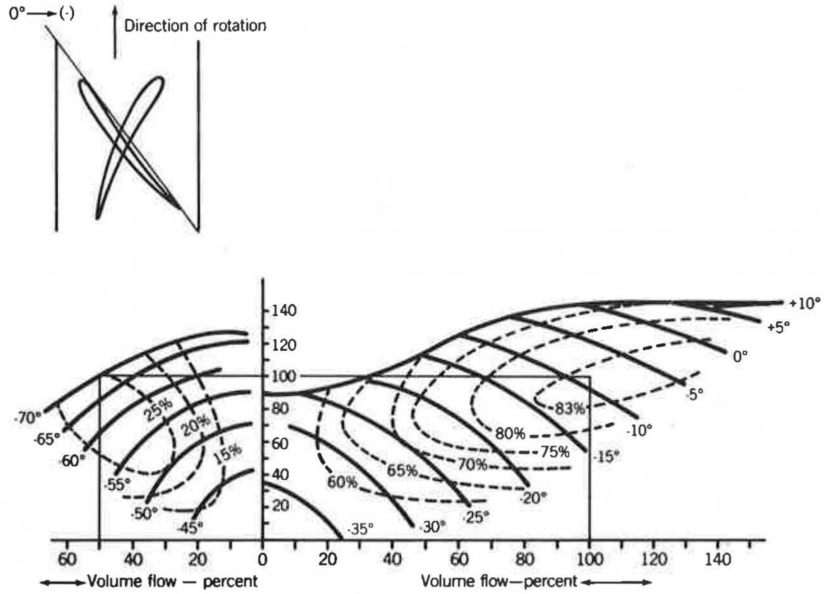
Maintenance

Routine maintenance is required for all fans, regardless of their design. On centrifugal fans, maintenance is normally limited to main bearings, motors, and belt drives. On axial flow fans, as shown in Figure 6, maintenance is required for the motors, blade shaft bearings, and the hydraulic blade-adjustment mechanism (Figure 7), as well as the hydraulic oil supply units.

Well-designed axial flow fans have split fan housings that have a section for easy and fast removal to provide access to all interior components. The interior components are designed for quick removal. A spare unit, which consists of a rotor, motor, and hydraulic blade-adjustment mechanism, should be maintained in stock so that, in case of a premature failure, a fast exchange can be made.

Maintenance cost on axial flow fans will be somewhat higher than on centrifugal fans. This factor should be considered in the overall evaluation.

Figure 8. Reverse flow through blade overturning.



Noise

Emitted fan noise is essentially a function of fan rotor tip speed, pressure developed by the fans, power consumption, and number of fans operating in parallel. The highest sound pressure level will be found at the blade-passing frequency of the fan rotor.

Although centrifugal fans for tunnel ventilation systems usually have eight blades, well-designed axial flow fans will have four to six blades. Despite the higher operating speed of axial flow fans, their blade-passing frequency will not exceed that of centrifugal fans.

The disadvantage of an axial flow fan remains with its higher tip speed; e.g., on a one-to-one comparison, the emitted noise level of an axial flow fan will be higher than that of a centrifugal fan. This disadvantage, however, is eliminated when a system of three centrifugal fans operating in parallel are compared with a system of two axial flow fans operating in parallel. In conclusion, it can be stated that neither fan design will offer an advantage.

Vulnerability to Tunnel Fires

To discuss a fan's resistance to high temperature, it is necessary to first identify all critical fan components that will be exposed to such high temperatures.

Regarding centrifugal fans, the main shaft and the complete rotor will be exposed. To design these components for high-temperature resistance will require expensive special alloy steels that will substantially increase the fan costs, especially when one considers the affected component sizes and the number of fans.

On axial flow fans, the only directly affected components are the fan blades. To build the blades from special alloy steel is easily possible. Although the fan cost will increase substantially, it will be disproportionately less than for centrifugal fans, considering that only four to six blades per fan are required and fewer fans are needed.

All other components of the fan are well protected in the fan hub center. The fan hub can be heat insulated and purged with cooling air.

Another beneficial feature inherent to VPAFFs is that the blade pitch can be reversed, thereby causing reversed flow (see Figure 8). This feature may provide an added tool to control tunnel fire. In conclusion, it is safe to say the VPAFFs have a greater flexibility to meet upset tunnel ventilation conditions.

SUMMARY

VPAFFs have been used for tunnel ventilation applications in Europe for the past decade. Today's state-of-the-art design is the end product of consistent fan component design improvements based on operating experience. The reliability and recorded availabilities easily match those of conservatively designed centrifugal fans. The basic advantages of power savings, which result in reduced operating costs, and small physical size and lower number of operating equipment, which reduce capital investment requirements, make this fan a viable alternative to centrifugal fans for tunnel ventilation systems.

Fort McHenry Tunnel Ventilation System

PAUL K. HINKLEY

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.

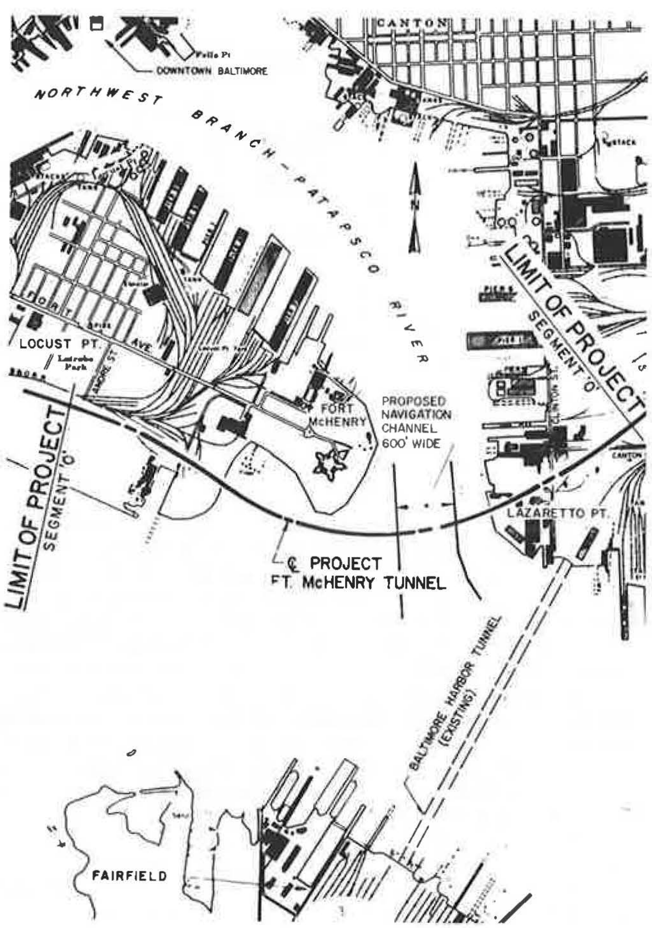
5. Direction of traffic: Each tunnel tube will carry two lanes of one-way traffic, and this direction will not be reversed.

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.

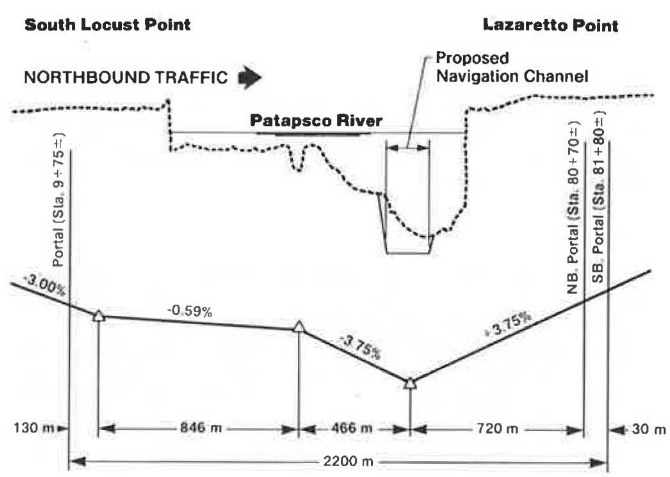


Figure 3. Tube sections.

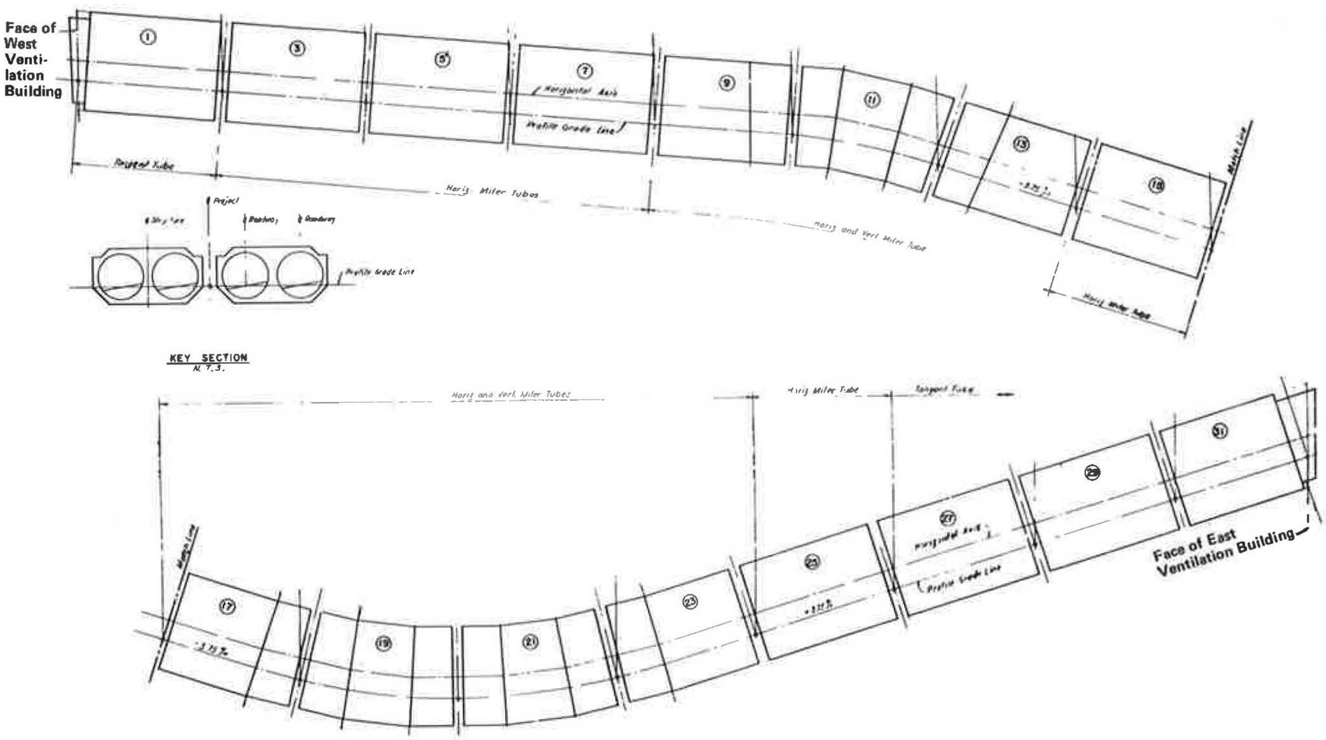
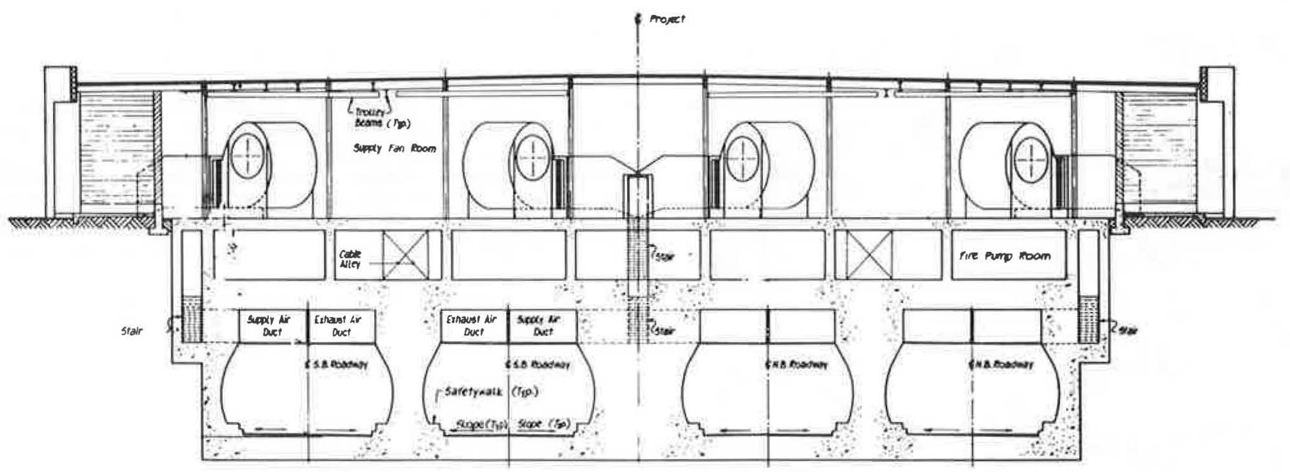


Figure 4. West ventilation building, land section.



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-

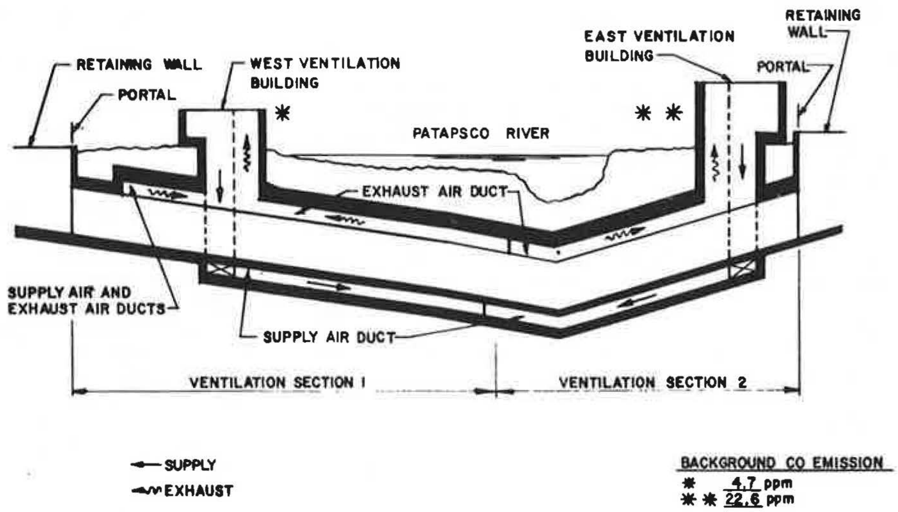


Figure 5. Typical longitudinal section.

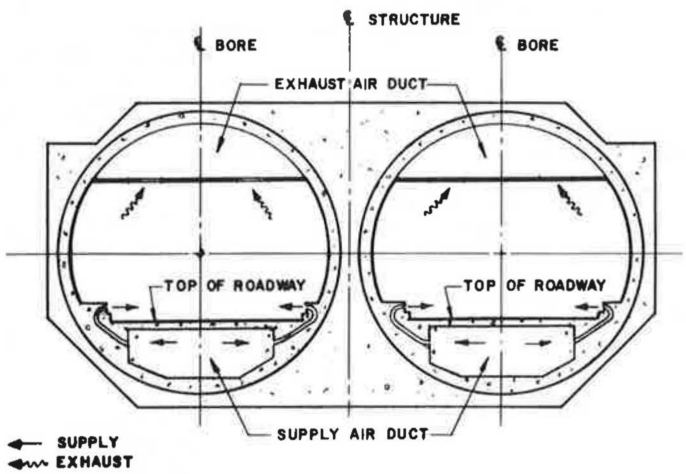


Figure 6. Typical tube cross section.

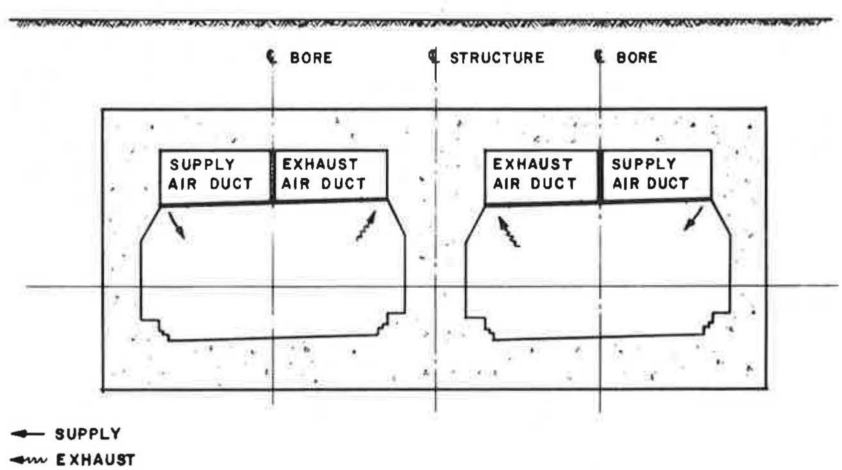


Figure 7. Typical cut-and-cover section.

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 in the figure the full-line curve represents average values and the broken-line maxima is for normal observers.) It is significant to note that in the first few seconds, adaptation is rapid; later, after a lapse of approximately 8 min, there is an intersection between two curves where the transition from cone (photopic) vision to rod (scotopic) vision takes place.

The time duration required for dark adaptation also depends on the luminance levels to which the eye was exposed prior to the beginning of dark adaptation. Dark adaptation has a pronounced influence on visual acuity, depth perception, and contrast sensitivity. All of these factors are of great importance in the visual process of night driving.

Adaptation Physiology

The immediate physical eye reaction to change in luminance levels is represented by pupillary dilation and contraction. From the size of the opening of the pupil, which varies between 2 and 8 mm in diameter, the quantity of light that reaches the retina will be determined. The quantity of light will influence the strength of signals generated within the retina following a photochemical reaction.

Although the pupillary change has specific significance in the adaptation process, the size of the opening does not represent the actual state of dark adaptation at any specific moment. In the first few seconds of adaptation, the process is very rapid (Figure 1). However, the time required for the pupil to open from 2 to 8 mm is of the order of 10 s. Although 10 s is not nearly of sufficient duration for reaching retinal stability, in practice it is believed that such time is of considerable significance (4).

In designing the tunnel-lighting system, the length of the supplementary zone is related by some researchers to the period required to achieve complete pupillary dilation. It is believed that the equivalent travel time from the beginning of the driver's fixation on the tunnel entrance (150 m) and the length of the supplementary lighting zone should be not less than 15 s.

Preadaptation and Transient Conditions

In analyzing the visual process that affects the adaptation state prior to the tunnel entrance, two specific positions should be noted. These are the fixation point and the adaptation point.

The first point describes the driver's position when he or she registers awareness of a visual obstacle. At a distance of 150-200 m [Figure 2 (5)], the dark outline of the tunnel entrance becomes a factor within the driver's visual field and begins to influence the state of adaptation (6,7). As the distance between the driver and the tunnel entrance is reduced, the relative size of the entrance outline increases, thereby forcing an adjustment in pupillary dilation.

The second point is when most of the principal field area is occupied by the tunnel opening, which affects the pupillary dilation, thereby resulting in definite and forceful adjustment. This position is often called the adaptation point. The adaptation point for a conventional-type tunnel will be at a distance of approximately 10-15 m from the entrance.

The degree of difficulty in visibility at this point will depend mainly on the conditions in the tunnel threshold zone. If the level of illumination in the tunnel interior is very low, adaptation will be difficult and the flow of visual information will be interrupted.

AMBIENT ILLUMINANCE LEVELS AND L_1:L_2 RATIO

The ambient illuminance levels were measured by Ketvirtis in 1972 for the months of June, July, and August. Four readings were taken (9, 11, 13, 15 h) every second day during these months. Figure 3 shows the results of the readings. From these readings, it is evident that the illuminance level can exceed 120 000 lx; with a reflectance coefficient of 25 percent, the ambient luminance may reach 10 000 cd/m². [Ed. note: For an approximate conversion of lux to footcandles, use a ratio of 10:1.]

EXISTING STANDARDS FOR TUNNEL-LIGHTING DESIGN

Because each tunnel design varies with respect to its geometry, material use, construction methods, traffic characteristics, and geographic location, visibility conditions also differ in each individual case. Thus, it may appear futile to attempt to establish even some generalized guides for lighting design. But, in spite of all these differences in visibility requirements, several national and international technical organizations offer recommendations that give quantitative values of photometric characteristics for tunnel-illumination systems.

CIE Recommendations

In 1973, the Committee TC-4.6 of CIE prepared International Recommendations for Tunnel Lighting (1). Figure 4 (1) shows the suggested luminance values in the tunnel threshold and transition zones.

The current CIE recommendations are based on Schreuder's (7) investigations in the 1960s, which were mainly derived from laboratory experiments. According to these recommendations, the ratio between L_1 and L_2 should not exceed 10:1.

Narisada and Yoshikawa (5) repeated Schreuder's experiments and verified his results. The comparison of research results is shown in Figure 5. Based on the results of these experiments for the L_1 value of 8000 cd/m², it would be necessary to obtain a threshold zone luminance of 800 cd/m², or approximately a 12 000-lx illuminance level.

PIARC Recommendations

At the XV Road World Congress in 1979, a report was published by a technical committee on road tunnels that outlined the design recommendations for tunnel lighting (2). This committee conducted extensive theoretical studies, as well as field observations, at existing tunnels around the world. Their recommended ratio of L_1 to L_2 (or Lsp to Lsp') falls in the range of 15:1 to 30:1 [Figure 6 (2)]. The recommended length of L_2 (Lsp') is 50-80 m. Comparing the levels based on PIARC with those of CIE, note that there is a considerable difference. For example, according to CIE recommendations, if the value of L_1 = 8000 cd/m², then L_2 should be 800 cd/m². However, the PIARC value based on, say, a 25:1 ratio is L_2 = 320 cd/m². The cost of the difference between these two recommendations for a two-way divided tunnel can be of the order of $400 000.

CASE STUDY: THOROLD TUNNEL ILLUMINATION

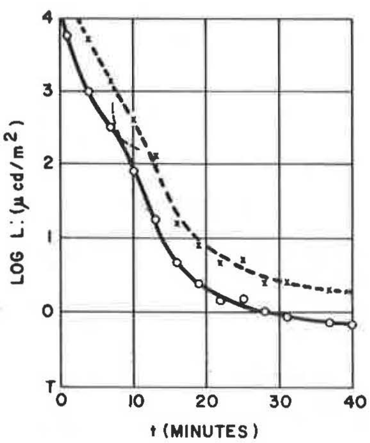
For the purpose of improving the illumination system at the Thorold Tunnel entrance, a study was conducted in 1976 by the Ministry of Transportation and Communications, Ontario, and Fenco Consultants, Ltd. The objective of this study was to investigate the practical lighting levels at the tunnel entrance and its interior related to the driver's visibility needs and sound economics (according to the Thorold Tunnel Visibility Study, 1976, an internal report by the Ministry of Transportation and Communications, Ontario, and Fenco).

Investigation of Existing Tunnel Lighting Prior to Thorold Tunnel Study

Prior to commencing the Thorold Tunnel study, a number of tunnels in Canada, the United States, Great Britain, and Western Europe were visited, and observations were made regarding the effectiveness of the lighting in the threshold zone.

Observations at the Vlake Tunnel, Holland, were carried out on October 5-6, 1976, with the permission of the Ministry of Transport, Holland. This

Figure 1. Adaptation curve.



Note: L = threshold illuminance and t = time.

Figure 2. Fixation, distance and frequency.

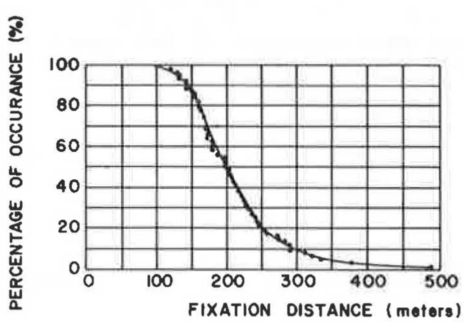


Figure 3. Horizontal illuminance distribution for June, July, and August 1972, 43° latitude.

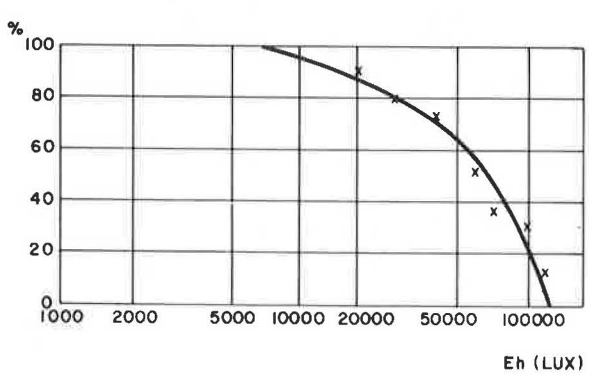


Figure 4. Recommended decrease of luminance values in entrance zone.

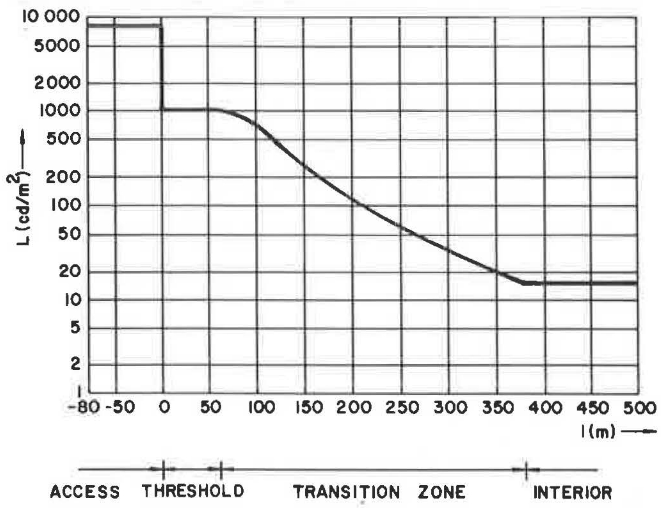


Figure 5. Ratio between L_1 and L_2.

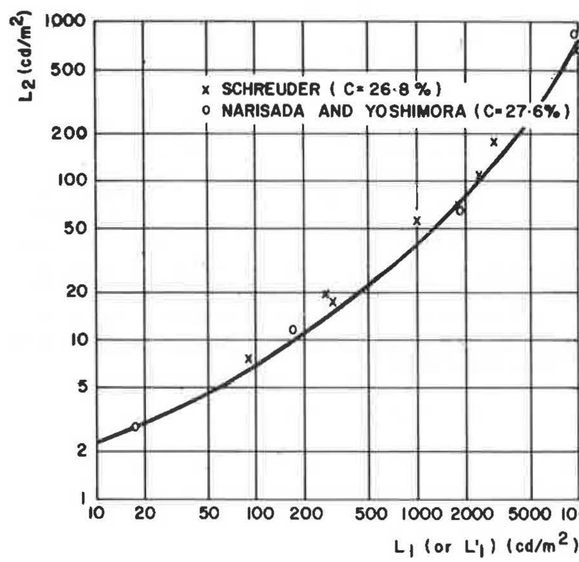
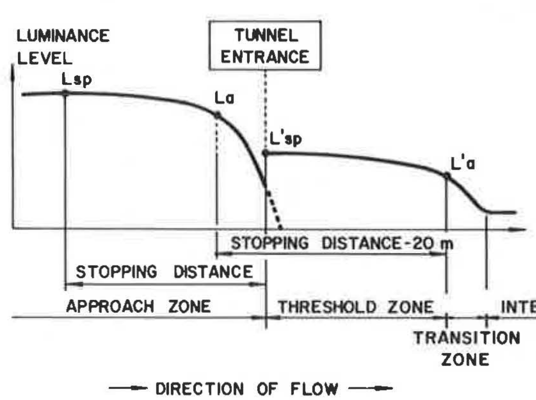


Figure 6. Recommended relation between Lsp and Lsp'.



tunnel was of particular interest to the investigators because of its similarity to the Thorold Tunnel (east-west orientation and the tunnel crossing a waterway).

The lighting system in the threshold zone for this tunnel is designed to provide the following lighting levels: 6200, 3000, 1500, 600, and 300 lx. With an outdoor illumination (L_1) of 48 000 lx, a brown compact car was observed in the tunnel interior from a distance of 100 m. The following table gives the results of the observations:

Lighting (lx)	Result
300	Car not visible in tunnel
600	Car not visible in tunnel
1500	Car barely visible
3000	Car clearly visible
6200	Visibility excellent, but improvement was not significant for observations on an overcast day

Observations and Measurements at Thorold Tunnel

The construction of the Thorold Tunnel, which crosses a shipping canal near St. Catharines, Ontario, was completed in 1968. It consists of two tubes, each carrying two-lane traffic, and has a posted speed of 72 km/h.

The initial illumination level (1968) in the threshold zone was approximately 1000 lx by using mercury vapor lamps for supplementary lighting and fluorescent lighting for the tunnel interior. In 1976, measurements were carried out at the tunnel site. A summary of the findings is given below:

1. The level of illumination in the threshold zone was measured at 300 lx. After cleaning the luminaires and relamping, the level was raised to 900 lx.
2. The visibility into the tunnel interior at the critical distances from the portal does not provide a 100-m safe stopping sight distance, particularly if the ambient luminance level is high (i.e., bright summer days).
3. Visibility distance is also reduced by a sharp vertical drop in the approach road (west end) and in the interior road alignment.
4. The white portal facing, which acts as a reflector in the morning at the east end and in the afternoon at the west end of the tunnel, has a negative effect on the driver's visual adaptation process.
5. The sun's low position in the morning and late afternoon penetrates the tunnel interior and interferes with the driver's vision.

After careful consideration of the results of the investigation, the following remedial measures were recommended to improve the existing conditions of the tunnel entrance and approaches:

1. The level of illumination in the threshold zone should be increased from the existing level of 900 lx to a maintained value of 3000 lx.
2. The tunnel portals at both ends should be treated with a dark, low-gloss paint.
3. When resurfacing of the approach roads is warranted, the concrete paving should be changed to a black high-friction type on the approaches and to a mix that has a high percentage of suitable white aggregate additive in the tunnel interior.
4. Planting suitable evergreens on the slopes near the entrance should be considered for the purpose of reducing reflectance of the snow-covered areas within the principal visual field.
5. Lighting equipment should be maintained in good operational condition.

SUMMARY OF DESIGN CRITERIA FOR NEW LIGHTING SYSTEM

As a result of the field measurements and observations, it was decided to redesign the tunnel-lighting system. In the process of establishing the design criteria for the new lighting system, the following factors were taken into account:

1. Traffic safety requirements (safe stopping sight),
2. Traffic operation requirements,
3. Possibilities of reusing existing lighting equipment,
4. Limitations in the existing transformer capacity,
5. Energy conservation,
6. Space limitations in the tunnel interior available for luminaire mounting,
7. Restriction in drilling of precast ceiling slabs and tunnel walls,
8. Need to wash the tunnel walls with high-pressure water hoses,
9. Pavement reflectance and skid characteristics, and
10. Maintenance factors and procedures.

From the visibility study by the Ministry of Transportation and Communications, Ontario, and Fenco, the requirement of the illuminance level for safe traffic operation in the threshold zone was determined to be 3000 lx. The total length of the threshold and transition zones was recommended to be 250 m. In order to meet the adaptation needs, it was necessary to design the system so that, for the first 80 m, the level was maintained at the same intensity of 3000 lx and the rest of the supplementary zone tapered off to meet the level of the tunnel interior lighting provided by the existing fluorescent lighting system. Supplementary lighting switching controls were implemented by photocell relays and arranged in three steps--3000, 2000, and 1000 lx. A review of the tunnel-type luminaires offered by the manufacturers and the light source analyses with respect to the efficacy and glare control led to conclusions that the most suitable source for this application was high-pressure sodium.

FIELD MEASUREMENTS OF ILLUMINANCE LEVELS: NEW SYSTEM

On November 30, 1979, field measurements were carried out at the tunnel threshold zone. The initial readings of illuminance levels are shown in Figure 7 (curve A). The estimated maintained illuminance level, with all luminaires energized (high level), is represented by curve B. Recommended values are indicated in curve C.

The values of maintained illuminance levels were arrived at by applying a maintenance factor of 0.4. Luminance readings were not taken at that time because the pavement resurfacing had not yet been carried out.

On April 1, 1980, a second field visit was made. The measurements of supplementary illumination indicated that the average level of lighting in the threshold zone dropped to approximately 5000 lx with all luminaires switched on. (The initial reading at the same location was 8000 lx. This indicates that the severe maintenance factor of 0.4 used in the calculation procedures is justified.)

SUMMARY OF OBSERVATIONS

On November 30, 1979, observations were carried out on the performance of the new lighting system, which included the following:

1. Observations of regular traffic flow and the patterns in change of speed, use of brakes, hesitation, and/or other irregularities at the Thorold Tunnel approaches and entrances;
2. The visibility conditions regarding eye adaptation from a moving vehicle;
3. Illuminance level measurements of the new supplementary lighting system; and
4. Photographic survey of visibility conditions at the approaches and tunnel interior.

From the observations and measurements conducted by a committee of lighting engineers, the following conclusions were made:

1. The new lighting system (at the time of observation) provides clear visibility into the tun-

Figure 7. Thorold Tunnel relighting.

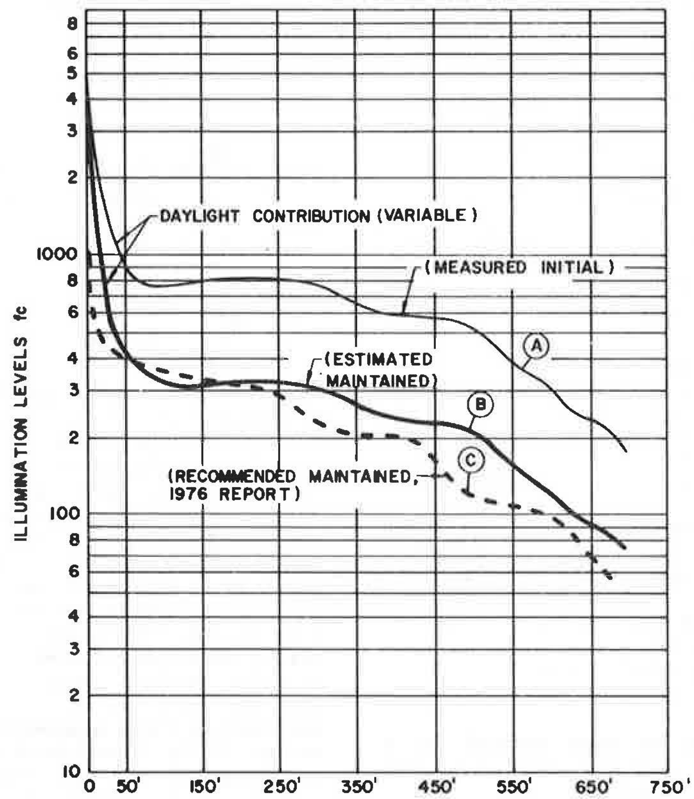
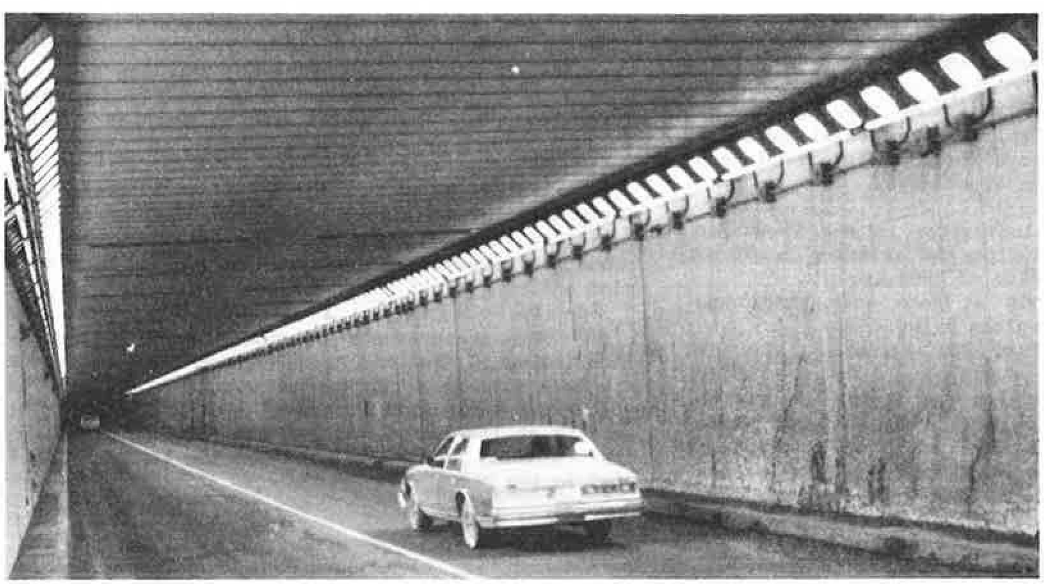


Figure 8. New lighting system in Thorold Tunnel.



nel, and an approaching driver with normal vision should have no problems in the eye-adaptation process (Figure 8) at the following lighting levels: L_1 = 68 000 lx and L_2 = 2600 lx; therefore, the $L_1:L_2$ ratio = 26:1.

2. The vehicles approaching the tunnel do not show any hesitation and very few drivers use their brakes at the tunnel approaches.

3. The new supplementary lighting system is acceptable from an aesthetic viewpoint.

4. The luminaire design features are compatible with tunnel operating conditions and maintenance procedures (i.e., washing with fire hoses).

5. The ambient (L_1) lighting level for this area exceeds 100 000 lx; therefore, with a maintained illuminance level in the threshold zone of the order of 3000 lx 95 percent of daytime, the ratio of $L_1:L_2$ is equal to 33:1. However, for short periods, the $L_1:L_2$ ratio may reach 40:1, but this is not considered too critical.

CONCLUSIONS

From the observations carried out at the Thorold Tunnel, it was concluded that a luminance level of 200 cd/m² or 3000 lx is adequate to secure clear visibility into the tunnel interior. On the very bright days of summer, therefore, the $L_1:L_2$ ratio may reach 40:1 without endangering the visibility conditions.

From these observations, it was learned that the value of the $L_1:L_2$ ratio changes with the increase of the L_2 value. At the lower ambient luminance levels (on cloudy winter days), the ratio between L_1 and L_2 should be lower (perhaps not exceeding 20:1). However, in the summertime when the L_2 value is higher, the ratio can reach 40:1.

In the design process, perhaps a ratio of 25:1 should be considered as reasonable and economically acceptable. It should be noted that this value also agrees with PIARC recommendations.

One further remark should be made regarding the basic principles currently used to describe tunnel lighting. The CIE and PIARC approaches refer to the ratio between L_1 and L_2 as the basis for tunnel-lighting design. Because the values of L_1 and L_2 are expressed in candela per square meter, it is desirable that the tunnel interior walls and pavement be painted as light a color as possible. However, the objects in the tunnel interior are seen by surface details; therefore, the most important lighting aspect should be vertical illuminance rather than the background luminance. The question then arises whether the current concept based on the ratio between L_1 and L_2 is correct. Perhaps a design based on vertical illuminance principles would offer a better assessment of visibility conditions in the tunnel interior.

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