NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
SYNTHESIS OF HIGHWAY PRACTICE **31**

HIGHWAY TUNNEL OPERATIONS

RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- MAINTENANCE, GENERAL
- CONSTRUCTION AND MAINTENANCE EQUIPMENT
- TRAFFIC CONTROL AND OPERATIONS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. 1975

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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PREFACE

There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the engineering ideas of men faced with problems in their day-to-day work. Because there has been a lack of systematic means for bringing such useful information together and making it available to the entire highway fraternity, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize the useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series attempts to report on the various practices without in fact making specific recommendations as would be found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available concerning those measures found to be the most successful in resolving specific problems. The extent to which they are utilized in this fashion will quite logically be tempered by the breadth of the user's knowledge in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis is recommended to engineers and others concerned with managing the operation and maintenance of major highway tunnels. Engineers who become involved in the design and construction of new tunnels also may find the synthesis useful. Detailed information is presented on how the special problems of traffic control and routine maintenance in tunnels are being combatted. Attention is given to the problems of operating and maintaining lights and light sources, and ventilating equipment.

Administrators, engineers and researchers are faced continually with many highway problems on which much information already exists either in documented form or in terms of undocumented experience and practice. Unfortunately, this information often is fragmented, scattered, and unevaluated. As a consequence, full information on what has been learned about a problem frequently is not assembled in seeking a solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem. In an effort to resolve this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of synthesizing and reporting on common highway problems—a synthesis being identified as a composition or combination of separate parts or elements so as to form a whole greater than the sum of the separate parts. Reports from this endeavor constitute an NCHRP report series that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.

Highway tunnels, especially those that are long enough to require artificial lighting and ventilation, are expensive to construct and costly to maintain and operate. When construction alternatives are under consideration, the high cost of maintenance and operation of tunnels must be kept in mind. Restricted lateral and vertical clearances greatly magnify the undesirable consequences of vehicle stalls and traffic accidents. The devastation that can result from fire unless quickly extinguished must always be a consideration. Lighting and ventilating equipment must be dependable and carefully maintained. The electronic surveillance and control equipment that is often used to enhance traffic operations must be selected and maintained with care to serve adequately. Preparedness to respond rapidly and effectively to a wide range of problems is of prime importance to success in tunnel operation.

This report of the Transportation Research Board records the current practice of a large number of agencies that operate and maintain highway tunnels. Guidelines are presented that past experience suggests will produce generally acceptable fulfillment of motorists' needs over a wide range of conditions.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from most of the agencies in the United States that operate large tunnels. A topic advisory panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. Meanwhile, the continuing process of search for better methods should go on undiminished.

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Valuable assistance in the preparation of this synthesis was provided by the Topic Advisory Panel, consisting of Michael J. Gittens, Assistant District Engineer, Pennsylvania Department of Transportation; Alan Gonseth, Assistant Manager, Lincoln Tunnel, Port Authority of New York and New Jersey; Elmo H. Orange, Toll Facilities Director, Virginia Department of Highways; Gary M. Roberts, Assistant Maintenance Engineer, Alabama State Highway Department; August J. Saccoccio, Director of Public Works, Town of Stratford, Connecticut; and James D. Washington, Tunnel Specialist, Office of Engineering, Federal Highway Administration.

Kenneth B. Johns, Engineer of Traffic and Operations, and Adrian G. Clary, Engineer of Maintenance, both of the Transportation Research Board, assisted the Special Projects staff and the Topic Advisory Panel.

Information on current practice was provided by many tunnel operators. Their cooperation and assistance were most helpful.

HIGHWAY TUNNEL OPERATIONS

SUMMARY

Highway tunnels carry automotive traffic through hills and mountains, and under water barriers, park land, and traffic bottlenecks. Operation and maintenance of these tunnels entail continuing problems and costs not encountered elsewhere on a highway—traffic problems are magnified, walls and ceilings need periodic cleaning, lighting must be on 24 hours per day, hazardous cargoes are restricted, and fresh air must be supplied for all conditions. An agency's operating policies will determine the extent of the problems and costs because these policies determine how much traffic delay is acceptable, what procedures are used for controlling ventilation and lighting, and how much dirt may accumulate before walls are cleaned.

The restricted lateral and vertical clearances are the primary causes of traffic problems. To minimize these problems many tunnels have some method for traffic surveillance and control. At several tunnels, personnel are stationed in the tubes to monitor traffic, report any incident, and render assistance. Many tunnels use television or vehicle detectors to enable an operator in a control room to monitor traffic flow and identify problems.

Almost all tunnels have signals at the portals to stop traffic in an emergency. Many also have overhead lane signals within the tubes. Variable message signs for traffic control are used within one tunnel and on the approaches to others.

Traffic stoppages in a tunnel occur at about the same rate as on open highways and are most often caused by vehicle breakdowns, occasionally by accidents, and less frequently by fires. Because a stoppage creates a serious traffic problem, special tow trucks are stationed at many tunnels to enable quick removal of any stalled vehicle. Usually, these trucks are also equipped for fire fighting.

Because the vertical clearance of most tunnels is less than on adjacent highways, overheight vehicles are a problem. Several tunnels use a photocell system, mounted at the maximum allowable height, to detect overheight vehicles.

Hazardous cargoes (explosives, corrosives, flammables, poisons) are prohibited from most tunnels although enforcement is difficult unless the vehicles are properly placarded and personnel are stationed at the tunnel entrance to watch for violations.

Washing of tunnels is necessary because tracked-in dirt and particles from vehicle exhausts are deposited on walls and ceilings. This results in decreased tile reflectance and therefore lowered visibility. Washing intervals are generally once or twice a month although some agencies wash weekly and others only semiannually. The frequency depends on traffic volumes and types, geometrics, weather, and other factors. Equipment used for washing generally consists of a detergent spray truck and a rinse truck. Some agencies use a brush truck between the detergent spray and rinse to scrub the wall or ceiling. At several tunnels, washing and other maintenance can be accomplished only at night because of high traffic volumes.

At many tunnels, burned-out lamps are replaced as they occur; at others all burned-out lamps are replaced at regular intervals, usually once a week. Group replacement of all lamps is also performed at some tunnels. Special platform trucks or bucket trucks are used for lamp replacement.

Most agencies report no problems in obtaining maintenance and operating personnel although a few say they cannot attract qualified people because of inadequate pay. On-the-job training is used by all agencies supplemented by manuals

and, in a few cases, special courses. Contract maintenance is used for certain specialized functions at many tunnels.

Two (or more) independent sources of electric power are available at most tunnels and each source is capable of providing full power for operation of lighting, ventilation, and pumps. Several tunnels have standby equipment (generators, batteries) in case all utility sources fail.

Tunnel ventilation may be transverse, semi-transverse, or longitudinal. In each case large fans are used to assure an adequate supply of fresh air in the tunnel. Air flow is controlled by changing the number of fans operating or the speed at which they run. Air flow is increased as monitoring equipment indicates increasing levels of carbon monoxide. At several tunnels the operator will increase ventilation in anticipation of increased traffic (such as before rush hour). Special procedures are available for ventilation operation in case of fire in the tunnel.

Operation and maintenance of a tunnel is far more expensive than other highway facilities. The least expensive tunnels have an annual cost of more than $50,000 per lane-mile for operation, maintenance, and electricity, and the costs range upwards to more than $900,000 per lane-mile.

A tunnel is the only practical solution for many situations and may be an alternate choice in others. When a selection is being made, the annual operating and maintenance costs should be kept in mind. If a tunnel is chosen, the design should consider the operating and maintenance problems and costs. Some specific considerations include:

- Lanes should be at least as wide as on approach roadways, shoulders should be provided where feasible, and vertical clearances should be the same as on adjacent highways.
- Equipment should be off-the-shelf insofar as possible.
- Standard sign colors and messages should be used.
- Hazardous cargoes should be restricted.

A tunnel is an expensive facility to construct, operate, and maintain. All possible steps should be taken to minimize expenses while providing proper service to the motoring public.

CHAPTER ONE

INTRODUCTION

Highway tunnels are used to carry automotive traffic through hills and mountains (Fig. 1). They are used under rivers and other water barriers where a bridge would not be practical (Fig. 2). Tunnels are also increasingly being used for other reasons—to eliminate bottlenecks (Fig. 3) or to preserve valuable park land or other real estate (Fig. 4).

However, the operation and maintenance of all except the very shortest tunnels entail continuing problems and costs that are not encountered elsewhere on a highway. Some of these problems are similar to normal highway problems but are of a different magnitude—for example, traffic operations, where the restricted clearances and lessened visibility greatly increase the usual traffic problems; and maintenance, where work must be done in a closed space, frequently under traffic. Many of the operations and maintenance problems are unique: periodic cleaning of walls and ceilings; lighting that is on 24 hours per day and,

Figure 1. Tunnel through mountain (Big Walker Mountain Tunnel, Virginia). (Courtesy of Va. Dept. of Highways)

Figure 2. Tunnel under water barrier (Baltimore Harbor Tunnel).

Figure 3. Tunnel to reduce traffic congestion (Lowry Hill Tunnel, Minneapolis). (Courtesy of Minnesota Dept. of Highways)

Figure 4. Use of tunnel to preserve a park (Lytle Park Tunnel, Cincinnati). (Courtesy of Ohio Dept. of Transportation)

in some cases, must be varied in intensity; restrictions on hazardous cargoes; simple vehicle breakdowns or accidents that block the roadway and are difficult to remove; and the myriad problems of assuring a supply of fresh air for all conditions.

The problems of urban tunnels are considerably different from those in remote rural areas, and unmanned tunnels have problems different from tunnels with a full-time staff. Even tunnels in similar environments may have differing problems depending on the length and design of tunnel, the volume of traffic handled, and, especially, the operating policies adopted by the responsible agency. These policies are important because they determine how much traffic delay is acceptable, what procedures are used to control lighting and ventilation, and how much dirt may accumulate before walls are cleaned. Naturally, these policies have a substantial effect on the costs of operation and maintenance.

There are nearly 100 tunnels of all types on United States highways today and more are planned and under construction. This synthesis is concerned with the tunnels (approximately 55) that are greater than 500 ft (150 m) in length and use artificial ventilation. Moreover, emphasis is placed on the major problems of operation and routine maintenance with little or no attention to major physical maintenance (pavement surface, structural elements, etc.) except as these affect operations.

The information for this synthesis was obtained from most of the agencies in the United States that operate tunnels. A summary of tunnel data is contained in Appendix B.

CHAPTER TWO

TRAFFIC OPERATION

The difficulties of traffic operation in tunnels are caused primarily by the restricted lateral and vertical clearances. These characteristics create problems such as complete lane blockage from vehicle breakdowns, restrictions on vehicle height, and the necessity of closing at least a full lane for any maintenance, however minor. The closed environment requires prohibition of hazardous cargoes and contributes to visibility problems at changes in alignment (curves, grade points). These operating difficulties are compounded by the apprehension experienced by some motorists when driving through a tunnel.

The traffic-carrying capacity of a tunnel is almost always lower than the capacity of other highways. This is because many of the factors that cause capacity reductions are usually present in a tunnel. These factors include restricted lateral clearances, reduced lane widths (in some tunnels), upgrades, considerable truck traffic, and reduced sight distances. The extent of capacity reduction is determined by the number of factors present and the extent to which the effects are offset by driver familiarity with tunnel conditions.

TRAFFIC SURVEILLANCE AND CONTROL

To minimize traffic problems, many tunnels, especially urban tunnels with high traffic volumes, have some method for continuous surveillance and control of traffic. The purpose is to maximize safe traffic flow by quick detection and response to any incident within the tunnel. The two general methods used for surveillance are personnel stationed within the tunnel and electronic devices.

Personnel

Personnel are stationed inside several tunnels, notably underwater toll facilities, to watch the traffic flow and handle any incident. Most of these tunnels have 24-hour manning of these positions although some reduce or elimi-

Some motorists are apprehensive when driving through a tunnel.

nate personnel in the tunnel between midnight and 6 a.m. The personnel are normally stationed in booths that have a fresh air supply from the tunnel ventilation system and are rotated on a schedule of 2 hours in the tunnel and 2 hours on the surface. Additional personnel may be used at the portals, particularly during peak periods.

The Brooklyn-Battery tunnel has four men in each tube 18 hours per day. In the Holland and Lincoln tunnels two men are used in each tube, 24 hours per day, and a third man during peak hours. They use special gasoline-powered vehicles (Fig. 5) that ride on the catwalk of the tunnel at speeds up to 25 mph (40 km/hr). Thus, two men can cover the area previously patrolled by six men and are able to move quickly through the tunnel to the scene of a problem or incident.

Several other tunnels have personnel assigned on a 24-hour basis but no one is stationed within the tubes. The personnel are located in a control room where their main function is operation and maintenance of the ventilation, lighting, and other equipment, but they will also respond to traffic problems.

Electronic Surveillance

Many tunnels—even those where there is no full-time staff at the tunnel—have some means of electronic traffic surveillance. Television and vehicle detectors are most commonly used.

Television enables an observer in a control room (not necessarily at the tunnel site) to see what is happening in the tunnel (Fig. 6). Several cameras are necessary for complete coverage of a long tunnel. To reduce the number of monitors to be watched, each monitor usually has a split screen with views either from two cameras or two views from one camera, achieved by use of mirrors. However, if a large number of screens is necessary, it is difficult to watch all of them at once. Thus a detector system is frequently used in conjunction with the television. For example, the Lincoln tunnel has loop detectors in the pavement connected to a computer that monitors the traffic flow. If any of several traffic stream characteristics varies from normal, an alarm is sounded. The appropriate television screens are indicated by an alarm light so the viewer can see what the problem is. A master monitor enables the viewer to select a specific camera for viewing.

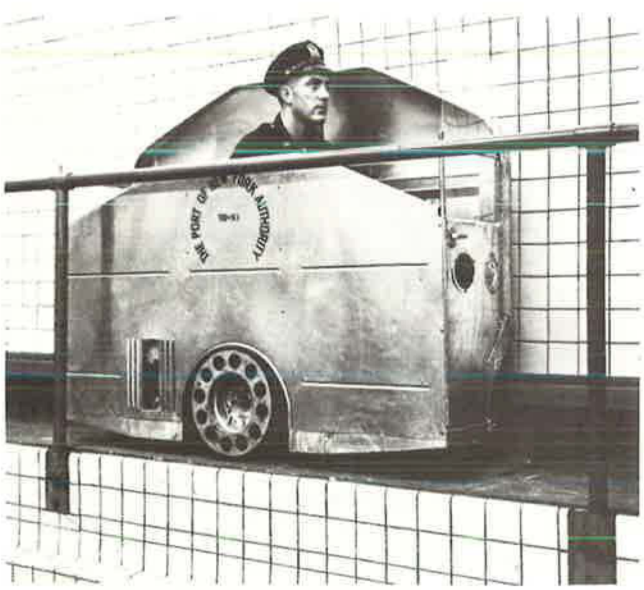


Figure 5. Special vehicle used by personnel in Holland and Lincoln Tunnels. (Courtesy of Port Authority of New York and New Jersey)

The Dewey Square tunnel in Boston has a sequential television system that shows a picture from each camera in sequence, holding the picture on the screen for about 5 seconds before automatically switching to the next camera. Three monitors are used for each tube, with seven cameras in one tube and eight in the other.

Television is used on the approaches to several tunnels to anticipate problems in the tunnel. Videotape facilities are available at a few tunnels to record stoppages and tests —these can be used for training purposes.

Television is not without its own problems, however. The picture is not of broadcast quality because of the environment in which the cameras must operate. A camera pointed at a portal tends to have the picture washed out during daylight hours. Cameras must be waterproof (a television system was removed from one tunnel because the wall-washing operation kept ruining the cameras) and periodic cleaning of the lenses is necessary.

The unmanned Green River tunnel in Wyoming uses a loop detector system connected to the local sheriff's office. If a stalled vehicle is detected, a warning light is flashed at the tunnel portal and an alarm is sounded in the sheriff's office. To verify that there is a stalled vehicle and not a brief stoppage, the operator waits 20 seconds and resets the system. If the warning light remains on, the procedure may be repeated (up to 3 minutes), after which a police car is dispatched. An ice detection system in the Green River tunnel automatically actuates flashers at the portal and sounds an alarm in the sheriff's office. A highway maintenance crew is then dispatched.

A computer at the Lincoln tunnel uses data from the loop detectors to control traffic flow and anticipate potential problems.

The Wallace tunnel in Alabama is equipped with television cameras and also microphones that enable the operator to hear the noise level in the tunnel. Normal background noise is suppressed by a squelch control. Unusual noises (above the threshold of the squelch control) call the operator's attention to a possible problem. Operators do not feel the noise system is useful and tend to rely on the TV system to spot problems.

Traffic Control

Almost all tunnels have signals at the portals to stop traffic in an emergency. These are either standard traffic signals or, more recently, lane-control signals with a red X and a green arrow. Most of the tunnels that have a surveillance system also have additional lane-control signals in the tunnel. Thus, if a lane is blocked, the signals for each lane can be set in a specific pattern best suited for expediting the handling of the incident and for moving traffic.

Variable message (matrix) signs, specially designed to fit in the limited space above the roadway are used in the Eisenhower tunnel in Colorado. Among the preprogrammed messages that can be displayed are: STAY IN LANE, STAY IN CAR, and HELP ON WAY. Changeable message signs are used on the approaches to the Caldecott tunnel in California, primarily to direct traffic into or away from the center (reversible) tube of the three-tube tunnel (Fig. 7). The signs are used in conjunction with compressed-air pop-up tubes in the roadway and a pop-up positive barrier to keep traffic from entering the wrong tube (Fig. 8).

Lighted or movable signs are used as additional traffic

Brooklyn-Battery Tunnel *(Courtesy Triborough Bridge & Tunnel Authority)*

George C. Wallace Tunnel *(Courtesy Alabama Highway Dept.)*

Figure 6. Control rooms with television monitors.

Figure 7. Changeable message sign at Caldecott Tunnel.

Figure 8. Pop-up barrier at Caldecott Tunnel.

Figure 9. Sign used to meter traffic at Lincoln Tunnel.

control measures within some tunnels. These include signs at grade change points to tell motorists to keep up speed or signs instructing drivers to stop motors because of congestion and carbon monoxide (CO) buildup. These signs may not be standard because there is little room in tunnels for standard signs. Several tunnel operators have reported that it is difficult to get motorists to pay attention to signs in tunnels.

Traffic is metered in the Holland and Lincoln tunnels to increase flow and reduce congestion. Given the same demand, it has been shown that metering can increase capacity by about 4 percent with a corresponding decrease in congestion of 33 percent. At the Lincoln tunnel, detectors and an on-line computer are used to monitor traffic. When it appears that optimum flow will be exceeded, signs at the portals are automatically changed to a PAUSE HERE—THEN GO message (Fig. 9). This has the effect of reducing input flow rate, without an abrupt halt to the entering traffic stream, and keeping flow within the optimum zone. The signs usually are activated for periods of 30 to 120 seconds.

The Baltimore Harbor tunnel uses an experimental fixed-time signal, based on historic data, that introduces a gap in the traffic stream to prevent oversaturation. This is the first step toward an automatic system.

STOPPAGES

Traffic stoppages within a tunnel are most often caused by vehicle breakdowns and accidents, and less often by fires and medical emergencies. Because of the confined nature of a tunnel, an event as simple as a flat tire can be a significant problem. Procedures should be available to handle almost any eventuality.

Vehicle Breakdowns

Vehicle breakdowns are by far the most common form of stoppage. They occur roughly in proportion to the tunnel length and traffic volume. The range of occurrence runs from 3 to 20 per 100,000 vehicle-miles (1.9 to 12/100,000 veh. km). This is about the same as was reported for open highway—4 to 22 per 100,000 vehicle-miles (2.5 to 14/100,000 veh. km).* A breakdown causes traffic problems, creates an accident potential, and should be removed as soon as possible.

At tunnels with continuous surveillance a stalled vehicle usually can be detected quickly and steps taken to remove it. Most of these tunnels have one or more tow trucks available and several have special short-wheelbase tow trucks that can tow almost any size vehicle (Fig. 10). These trucks can be turned around in the tunnel and are also equipped to fight fires. When the stoppage is determined to be caused by a stalled vehicle, a tow truck is sent into the tunnel (usually against traffic) and the disabled vehicle is then towed out. If the tunnel has lane signals, these will have been set to the proper pattern for emergency response.

Agencies that have towing equipment at the tunnel report that they make no repairs in the tunnel. The disabled vehicle is towed to a safe location outside the tunnel at no cost to the motorist. One agency will tow a car to an adjacent service station of the motorist's choosing. Others will give water and air, give or sell a small amount of gasoline, usually 1 gal (4 l) or less, and assist in the changing of flat tires. At the Brooklyn-Battery and Queens-Midtown tunnels in New York, the services of the local American Automobile Association (AAA) affiliate have been arranged for motorists needing assistance. The disabled motorist is towed from the tunnel without charge and is given a card with the AAA telephone number and the rates that will be charged for gasoline delivery, changing a flat tire, towing, and the like.

Most of the tunnels without surveillance systems have an emergency phone system that is connected to a highway or police office and can be used to summon aid.

Accidents

Accidents, generally of the rear-end or sideswipe type, occur infrequently in tunnels and usually involve only minor property damage. The range of accident rates varies from 200 to 1,500 per 100,000,000 vehicle-miles (120 to 930/100,000,000 veh. km). As a comparison, the over-all rate for the United States during 1973 was 1,270 accidents per 100,000,000 vehicle-miles (790/100,000,000 veh. km).

The response to accidents is similar to the response to vehicle breakdowns. Personnel at tunnels that have a full-time staff are trained in first aid and the tow trucks at the tunnels are equipped with first-aid kits. Arrangements are usually made with local hospitals and ambulances to respond when needed.

Fires

A fire in a tunnel is a potentially severe problem because of the difficulties of getting fire fighting equipment in, the heat and smoke in a confined space, and the potential panic of

* "Motorists' Needs and Services on Interstate Highways." *NCHRP Report 64* (1969) p. 8.

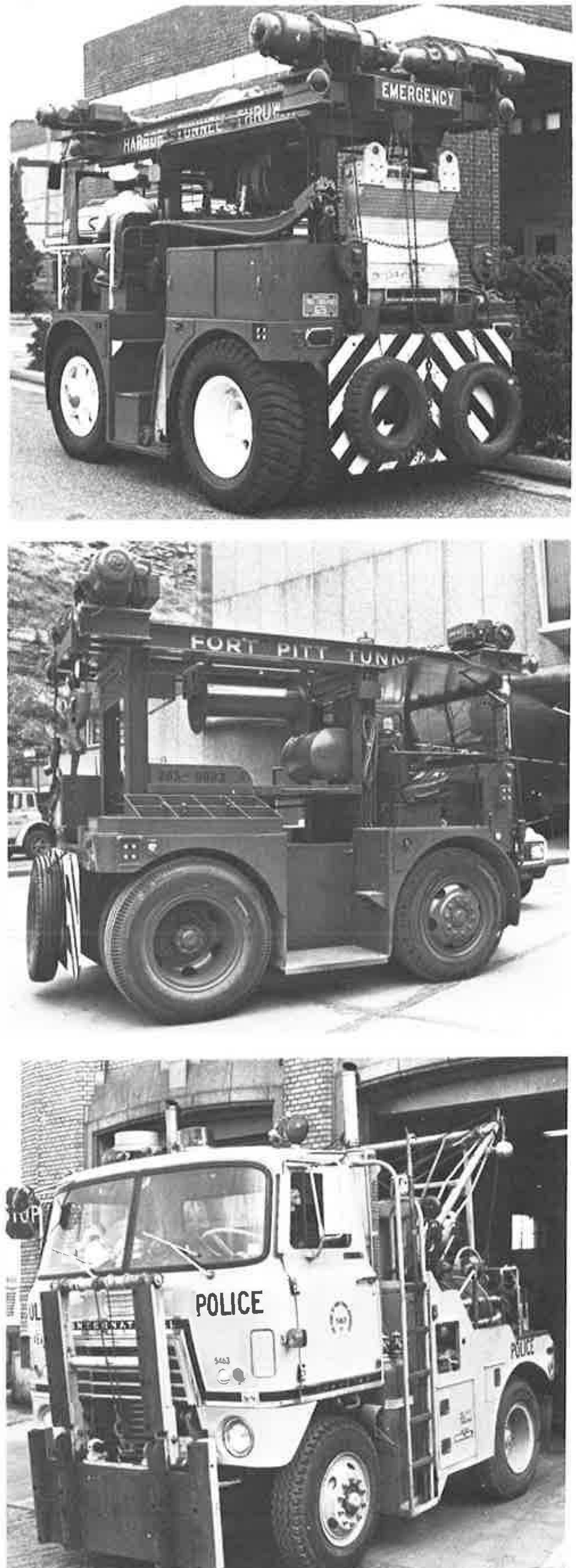


Figure 10. Special tow trucks for use in tunnels (Baltimore Harbor, Fort Pitt, and Holland Tunnels).

motorists trapped in the tunnel.* To prevent the occasional minor vehicle fire from becoming a major fire, all tunnels have some degree of fire fighting capability. Fire extinguishers are located in the tubes at intervals of 75 to 325 ft (23 to 100 m) (Fig. 11); tow trucks are equipped with fire extinguishers, hoses, and other equipment; some tubes have standpipes or hydrants, and personnel are trained in the use of the fire fighting equipment. The Eisenhower tunnel has a fully equipped fire engine with resuscitator, wreckage spreading jaws, cutting saws and torches, and other equipment.

Special procedures are used for operation of ventilation during a fire (see Chapter Five). Several tunnels have a sprinkler system in the air ducts to protect the fans.

An automatic sprinkler system for tunnel tubes has been used, but there are several potential problems involved: the situation and type of fire should be analyzed to determine the type of extinguisher before sprinklers are turned on; accidental triggering of the system could result in danger of collisions; and maintenance of these systems may present a problem. One tunnel, currently under design, will use a dry system that would be turned on only by a fireman at the scene.

* For a detailed description of the most well-known tunnel fire, see "The Holland Tunnel Chemical Fire," report by the National Board of Fire Underwriters (1949) 18 pp.

The Wallace tunnel has a sprinkler system in the portal sumps, a foam system in the mid-channel sump, and a sprinkler system in the air duct adjacent to the fans. Water-flow switches in the lines feeding these systems and fire alarm pull-boxes located throughout the tunnel are connected to the City of Mobile Fire Alarm Center and the fire department will respond if an alarm is activated.

Most agencies report that fires are a rare event, occurring about once a year, although a few reported more frequent occurrences ranging from 4 to 40 per year. These are almost all minor and are handled by the fire extinguishers in the tunnel or on tow trucks.

Medical Emergencies

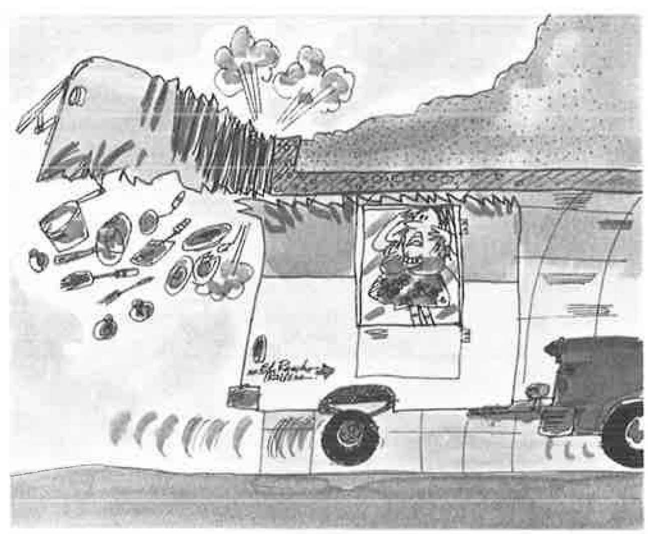
Medical emergencies, apart from injuries in accidents, are even rarer than fires, occurring well less than once a year. First-aid training and equipment are available where there is a full-time staff and some tunnels have additional equipment such as oxygen and inhalators. An ambulance is usually summoned, but if a person appears to be critically ill, transportation to the nearest hospital will be provided immediately by whatever means are available.

Some agencies report a problem that could be called a medical emergency. On occasion, a motorist has become so upset with fear of driving through a tunnel that he has stopped his car and either refused to continue driving or abandoned the vehicle in the tunnel and attempted to flee to "safety" on foot.

OVERHEIGHT VEHICLES

Many tunnels have vertical clearances that are less than clearances on adjacent highways; therefore, overheight vehicles are a problem. Damage to ceilings, light fixtures,

Figure 11. Niche in tunnel wall with fire extinguisher, alarm, and telephone.



Overheight vehicles are a problem at many tunnels and traffic signals has been reported. One means used by several tunnels to keep overheight vehicles from causing damage is an overheight vehicle detection system employing photocells. This system uses a light source and a photocell detector mounted on opposite sides of the roadway at the maximum allowable vehicle height. A vehicle that is higher than the limit breaks the beam, which sounds an alarm and, at some tunnels, turns the portal lights to red. The vehicle can then be measured and, if actually overheight, turned away. The photocell system is located at a distance from the tunnel portal that allows adequate stopping space. At some toll facilities, the system is located before the toll plaza so that an overheight vehicle can be stopped at the plaza. A problem with the photocell system is false alarms caused by trucks with loose canvas tops that billow up in the wind. Other problems are caused by snow and heavy rain.

The New River tunnel in Florida has an overhead sign mounted with the bottom edge at the tunnel clearance. At some toll tunnel plazas, a wood bar is hung from chains at the maximum height and the toll collector can see if a vehicle hits the bar. A trip wire at the maximum allowable height is used at the Midtown and Downtown tunnels in Norfolk, Va. An overheight vehicle will break the wire, sounding an alarm and turning the portal lights red. The wire has to be reset each time it is tripped. Some recently built tunnels with clearance of 14.5 ft (4.4 m) or greater report no problems with overheight vehicles.

HAZARDOUS CARGOES

Hazardous cargoes include explosives, corrosives, flammables, and poisons. Vehicles carrying hazardous materials are prohibited or severely restricted at most tunnels. These restrictions are based on the federal Motor Carrier Safety Regulations and the Hazardous Materials Regulations.* Several tunnels have their own publications, which follow the federal regulations. The restrictions or prohibitions are usually posted in general terms on approaches to a tunnel (Fig. 12) and carriers are expected to know the specific restrictions.

Minnesota has published a pamphlet for the Lowry Hill tunnel that gives general information on seven classes of prohibited and restricted materials. The pamphlet also has a map of tunnel bypass routes. For specific restrictions, carriers are referred to the federal regulations or to the state Bureau of Motor Carrier Safety.

The Port Authority of New York and New Jersey (Lincoln and Holland tunnels) has been the leader in developing comprehensive listings of restricted and prohibited materials. Other tunnels have used the Port Authority regulations as the basis for their own restrictions.

Enforcement of hazardous materials regulations is difficult unless the vehicle is carrying the required state and federal placards. Fortunately, most carriers follow the regulations and few violations are reported. Some tunnels have personnel at tunnel entrances to randomly inspect for violations, but not always on a 24-hour basis.

A few tunnels report that they have no posted restrictions on hazardous cargoes.

* Code of Federal Regulations, Title 49, Parts 397 and 170-189.

Figure 12. Hazardous cargo warning signs.

LANE CLOSURES FOR MAINTENANCE

The performance of any maintenance in a tunnel, such as washing of walls or lamp replacement, requires that a lane (or lanes) be closed to traffic because the maintenance crew must occupy a lane; few tunnels have full-width shoulders. In most cases only the lane occupied by the maintenance crews is closed and standard procedures are used for signing and coning a lane closure at the tunnel entrance. Flagmen and backup trucks are used as needed.

Sometimes an entire tube must be closed and two-way traffic operated in the other tube. However, this cannot be done in tunnels with semi-transverse or longitudinal ventilation systems, except when traffic is very light, because proper operation of the ventilation system depends on one-way movement of traffic.

The Lincoln and Caldecott tunnels, which have three tubes each, are able to close one tube for maintenance and still operate two lanes in each direction. The Lincoln tunnel, however, must close one tube at night because traffic volume requires all three tubes at other times. Because of high traffic volumes, most urban tunnels are able to close lanes for maintenance only at night.

COMMUNICATIONS

Communication to the motoring public consists of the signs and signals in the tunnel and at the portals, directions from personnel in the tunnel and at the portals, direct-line emergency phones, and public address systems. The public address system is used to advise stalled motorists to stay in their vehicles until help arrives. The Lincoln and Holland tunnels are experimenting with a wide-band AM radio transmitter that will permit public service broadcasts to cars in the tunnel—provided the car radio is turned on.

Some tunnels have a radio antenna so that motorists can listen to their car radios as they drive through. The antenna is located in the air duct, in the tunnel cove, or over the lanes if there is sufficient clearance. Reception is reported to range from fair to excellent.

Methods of communicating to persons working in tunnels include radio (reported to work well at some tunnels but not so well at others), telephone, paging devices, and coded light signals that tell a man to call the control room.

UNMANNED FACILITIES

Many tunnels have no operating and maintenance staff permanently stationed at the tunnel. Although it might be expected that this could lead to problems, it has not been reported to be the case, probably because the unmanned facilities are shorter—less than 2,000 ft (610 m)—and generally have lower traffic volumes. At a few unmanned tunnels, several functions are monitored from a remote point. The traffic and ice detection systems at Green River tunnel are monitored in the local sheriff's office. The Lowry Hill tunnel has a monitoring system that transmits data on 21 functions to a maintenance dispatcher 5 miles (8 km) away. This covers items such as power failure; excess CO; malfunction of analyzers, fans, or lights; fire; and unauthorized entry into the equipment building.

Emergencies at unmanned facilities are handled through the phone systems, which are direct connections to police or a highway dispatcher. Good response times (10 min or less) were reported.

Vandalism is considered to be minor. Reports included graffiti, some lights shot out, and a few fire extinguishers stolen.

CHAPTER THREE

GENERAL MAINTENANCE

TUNNEL WASHING

Dirt tracked into a tunnel by vehicles and particles from vehicle exhausts (especially from diesel engines) deposit on the walls and ceilings of the tunnel. This results in decreased tile reflectance and, therefore, lowered visibility. Periodically, then, the walls and ceiling must be cleaned.

Based on experience with the volume and type of tunnel traffic, most agencies make a determination of how often their tunnels should be washed. Some agencies use light-meter readings to determine loss of reflectance and thus the need for washing. The Wallace tunnel has a 15 percent loss of reflectance in two weeks.

Actual washing intervals are generally once or twice a month, although some agencies wash weekly and others semi-annually. The river tunnels in New York City, with their high traffic volumes and high percentage of trucks and buses, are washed weekly, weather permitting. The West Rock tunnel in Connecticut, with far lower traffic and no commercial vehicles, is washed only twice a year. The Caldecott tunnel is washed as needed—about once a month for the tube that carries truck traffic on an up-grade and once every three months for the other two tubes. The Fort Pitt tunnel is scheduled for 18 washes each year, but they are done only after an inspection is made to determine that the tunnel needs washing and if weather permits. Tunnels are not washed unless the temperature is above freezing.

Visibility is reduced by
deposits on tunnel walls and ceiling.

Figure 13. Tunnel washing equipment—detergent spray truck (Holland Tunnel)

Equipment used for washing varies. Most common are three special-purpose trucks for detergent, brushing, and rinse (Figs. 13, 14, and 15). The first truck carries a solution of detergent in water, which is sprayed on the wall (or ceiling). The brush truck then scrubs the wall (or ceiling) and is followed by the rinse truck, which sprays a clear water rinse. Some agencies use the brush truck on alternate washes only, and some do not use a brush truck at all. In these cases a few minutes are allowed for the detergent to soak in before the tunnel is rinsed. Sometimes two passes of the rinse truck are required. California has developed a single machine that applies the detergent, brushes a portion of the wall, and rinses with clear water in one pass. A few tunnels are cleaned manually with high-pressure hoses and long-handled brushes.

Four passes of the washing equipment usually are required—one for each wall and one for each half of the

Figure 14. Tunnel washing equipment—brush truck (Pennsylvania Turnpike).

Figure 15. Tunnel washing equipment—rinse trucks.

ceiling—except at tunnels where the ceiling is not cleaned. Because the area covered by the California machine is limited, it requires more passes to complete the cleaning.

Four to six men are generally used for the washing operations although the California machine needs only two. In each case an additional two or three men are needed for traffic control. Because of traffic problems, many tunnels are washed at night (10 p.m. to 6 a.m.).

Cleaning around television cameras, signs, signals, booths, and the like, poses special problems. Some hand cleaning is frequently necessary in these areas.

All agencies use some kind of detergent—usually biodegradable and noninjurious to personnel, automotive finishes, and tile. Although steam is reported to do an excellent cleaning job, it is rarely used because it takes too much time and is too expensive. Steam is still used by a few agencies once or twice a year for specialized cleaning, such as around lighting fixtures.

Although wash water on the roadway is a potential problem, most agencies report no real problem. In large measure, this is because of good traffic control procedures and the low traffic volumes when the washing is done. The wash water is carried out by the tunnel drainage system and, in most cases, into the local sewer system. The Eisenhower and Big Walker tunnels each have a treatment plant to treat wash water.

LAMP REPLACEMENT

Several different schemes are used for lamp replacement. In many tunnels relamping is performed as burnouts occur. In other tunnels, all burned-out lamps are replaced at regular intervals, usually once a week. A third method is relamping when a certain number or percentage of lamps have burned out. Another method is group relamping at intervals ranging from one to five years. Combinations of these schemes are also used. At the West Rock tunnel all lamps are replaced every five years, but individual burnouts are also replaced as they occur. In the Brooklyn-Battery tunnel all burned-out lamps are replaced once a week, but if two lamp carriers in a row (four lamps) are burned out they will be replaced immediately.

At a few tunnels, readings of the light levels are made periodically and compared to the original design values less a maintenance factor. The maintenance factor includes provision for allowable decreases in light level caused by depreciation of lamp output, dirt in and on luminaires, wall and ceiling dirt, a percentage of burned-out lamps, and deterioration of the fixtures. When the actual light level falls below the maintenance factor, corrective measures (such as relamping or tunnel washing) are taken.

Special trucks with fixed platforms, trucks with hydraulic platforms, or bucket trucks are used for relamping. For example, the Fort Pitt tunnel has a special platform truck with hinged work platforms on each side (Fig. 16). These platforms extend over the safety walks when in the "down" position and enable a man to reach the lamps easily.

Relamping operations generally require two or three men and possibly one or two more for traffic control.

Figure 16. Platform truck for lamp replacement (Fort Pitt Tunnel).

PERSONNEL

Most agencies report no problems in obtaining qualified personnel to maintain the equipment in their tunnels; however, a few report problems because the pay is inadequate to attract qualified people. Several agencies use contract help for certain items. The number of personnel assigned to a tunnel varies considerably depending on the length, volume of traffic, amount of contract help used, availability of other help, and the number of hours per day that the tunnel is manned. Because the personnel at most tunnels perform both maintenance and operating functions, it is impossible to ascertain the number required for maintenance. The total operating and maintenance staff (not including toll collection) varies from zero to more than a hundred. The agencies with zero use personnel primarily assigned to other duties for maintenance at the tunnel.

Training

On-the-job training is used by all agencies. Some also have courses available and many have a maintenance manual (or manuals) that covers the specifics of the various kinds of equipment. At the Lowry Hill tunnel, instructions were given by contractors, manufacturers, and suppliers before the state assumed operation. Suppliers of equipment at the Wallace tunnel were required to give instructions on operation and maintenance of their equipment before the tunnel was opened to traffic. These instructions were taped and are available to help train future employees. Videotape is used at the Lincoln tunnel to train personnel in emergency procedures. Training is also necessary each year to familiarize tunnel tow truck operators with procedures for towing new and unusual cars.

Contract Help

Contracts for various facets of tunnel maintenance are quite common. They are frequently used because an agency does not want to hire someone for certain specialized functions that are not performed every day.

Annual inspection and calibration of carbon monoxide analyzers and recorders is often contracted even though a monthly calibration will be done by the agency's own forces. Tunnel washing is sometimes done under contract; one agency contracts only for the brush truck with crew. Other items performed under contract at various tunnels include: inspection (and repair, if necessary) of the entire electrical system; recharging of fire extinguishers; repair of television surveillance system; maintenance and relamping of lighting (usually by the utility company); and repair of fans and motors in the ventilation system—especially rewinding of motors.

NIGHT WORK

Because of the high traffic volumes at many urban tunnels and because a lane must be closed for any work in the tunnel, considerable maintenance work is performed at night. Washing and lamp replacement are commonly done at night. Pavement and lighting repairs are also made at night. Several agencies feel that working at night is safer because drivers entering a well-lighted tunnel from the darker highway can see men and equipment more easily than when going from daylight to a darker tunnel.

SEEPAGE

Although a few agencies report no serious problems with water seepage, most have at least minor problems. Seepage causes unsightly mineral deposits on walls, and in one tunnel icicles form during winter months.

Attempts to stop seepage have not always been successful. Several agencies have achieved some success with a chemical gel that is pumped behind the tunnel liner. Others use some form of grout. One agency seals the surface of hairline cracks with epoxy and then pumps additional epoxy through the tunnel liner. They report that this procedure results in the seepage starting elsewhere. Other procedures used include diversion dams and channels to remove surface water, and collection and disposal of water through the tunnel drainage system.

OTHER MAINTENANCE

Routine and preventive maintenance is performed to keep equipment in good condition. The functions include oiling of fans, motors, and the like; cleaning of drains; testing; painting; and inspections, as required. Most tunnels have a routine patrol several times a day and complete inspection of all systems at least annually.

Many tunnels have a stock of spare parts, particularly for specialized equipment such as fans, CO analyzers, motor controllers, and tunnel lighting.

CHAPTER FOUR

LIGHTING AND POWER SUPPLY

LIGHTING

Tunnel lighting operates continuously 24 hours a day throughout the year. Because of the great difference in brightness between daylight and the inside of a tunnel, an entrance zone usually has brighter lighting than the interior. The length of entrance transition lighting varies from 500 to 1,500 ft (150 to 450 m).

At night the transition lighting is often reduced to the same level as the rest of the tunnel, although some tunnels use the same light levels for day and night. The lighting is reduced by turning off the additional lights used at the entrance or by reducing their level. In some tunnels the interior lighting is also reduced at night. Reduction is controlled automatically by timers or photocells, although manual control is available. Some methods used are shown in Figure 17. The electrical switchgear and controls for lighting and ventilation are shown in Figure 18.

POWER SOURCES

Most tunnels have two independent sources of electric power—usually from separate substations of a single utility company. Each source is capable of providing power for complete operation of the tunnel lighting, ventilation, pumps, and the like. The Lincoln and Holland tunnels are fortunate in having totally independent sources at each end of the tunnel and each source provides three separate feeds. Figure 19 shows the control room of the Holland tunnel where the power feeds are monitored.

At most tunnels each power source normally supplies half the tunnel's power requirements. If one source should fail, the other source will take up the load. At some tunnels the switch is automatic; at others an operator must make the change.

Several tunnels have standby equipment in case all utility sources fail (Fig. 20). The standby equipment varies at each tunnel. The Broadway tunnel has a battery system that will operate only emergency lights in the offices and

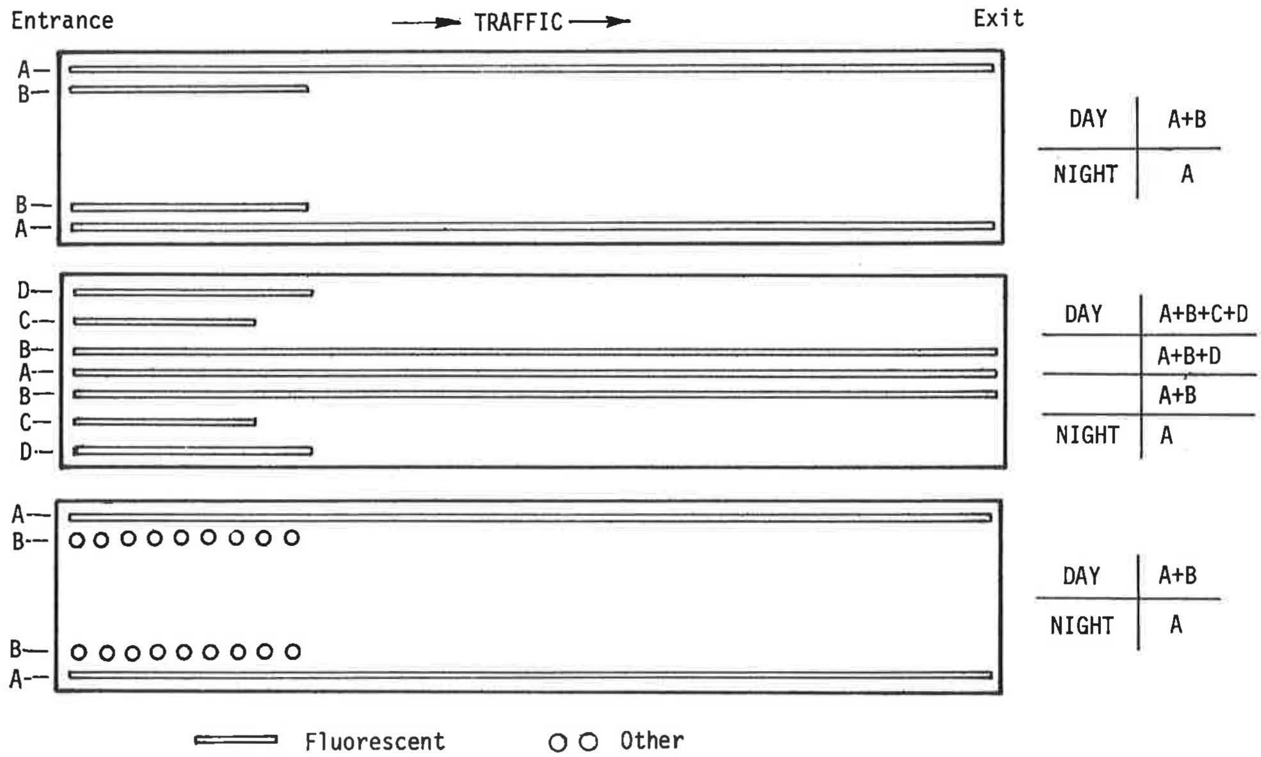


Figure 17. Typical methods of operation for tunnel lighting.

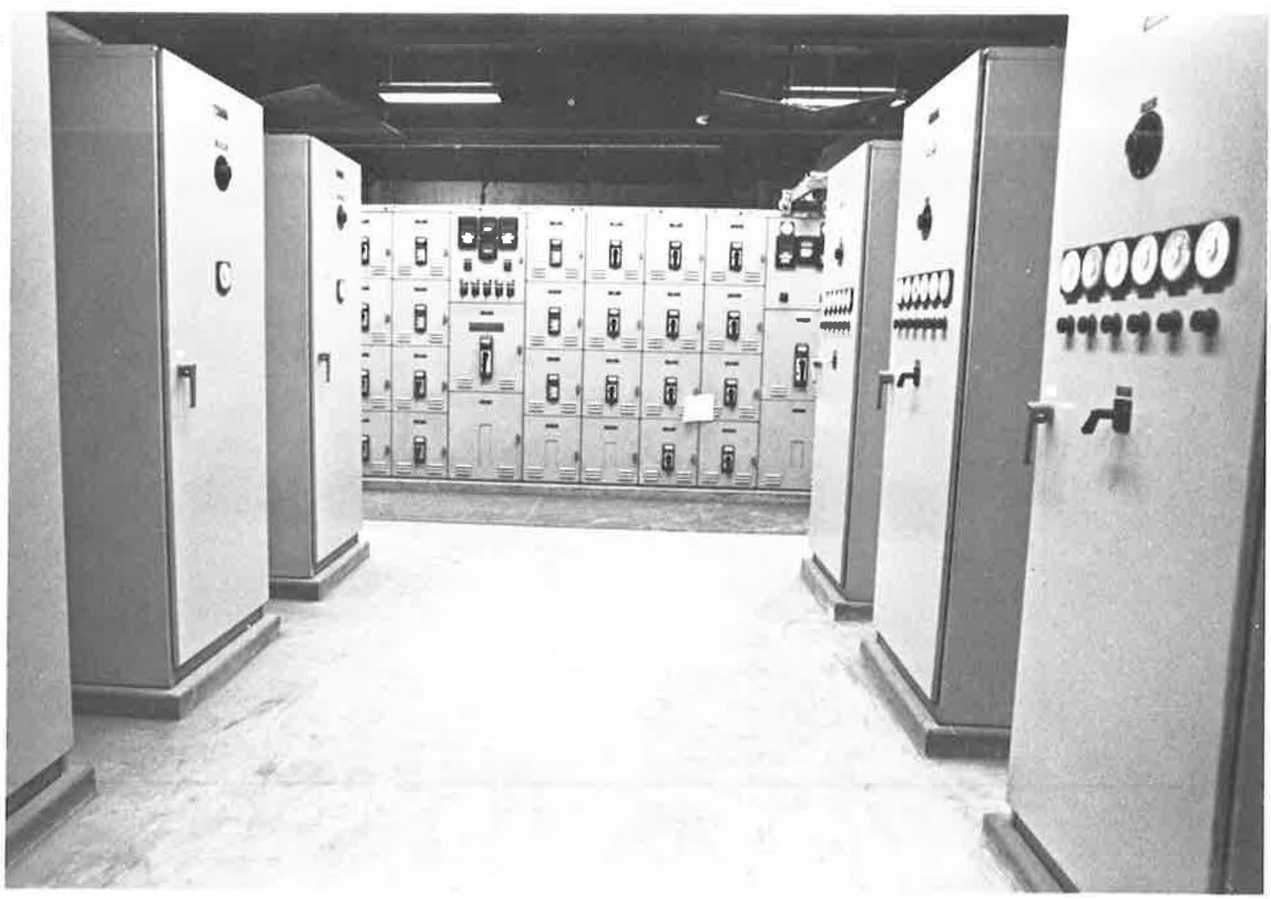


Figure 18. Electrical switchgear for lighting and ventilation (Fort Pitt Tunnel).

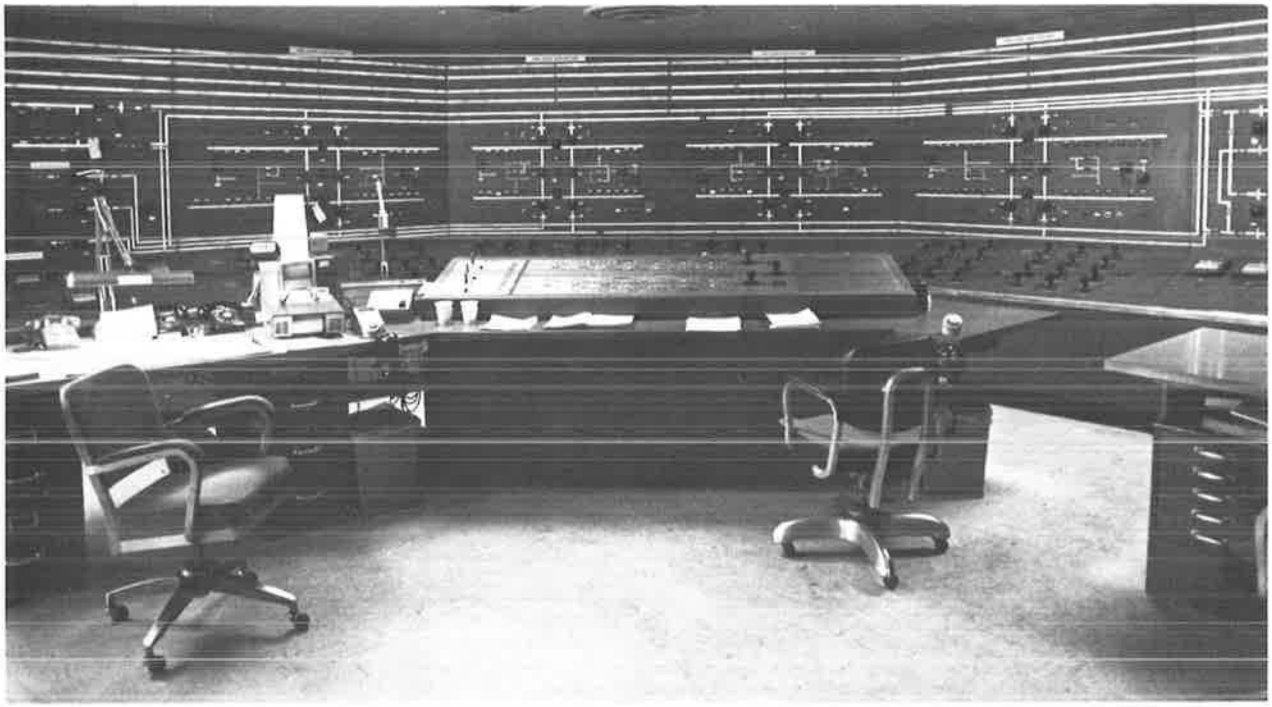


Figure 19. Control room (Holland Tunnel).

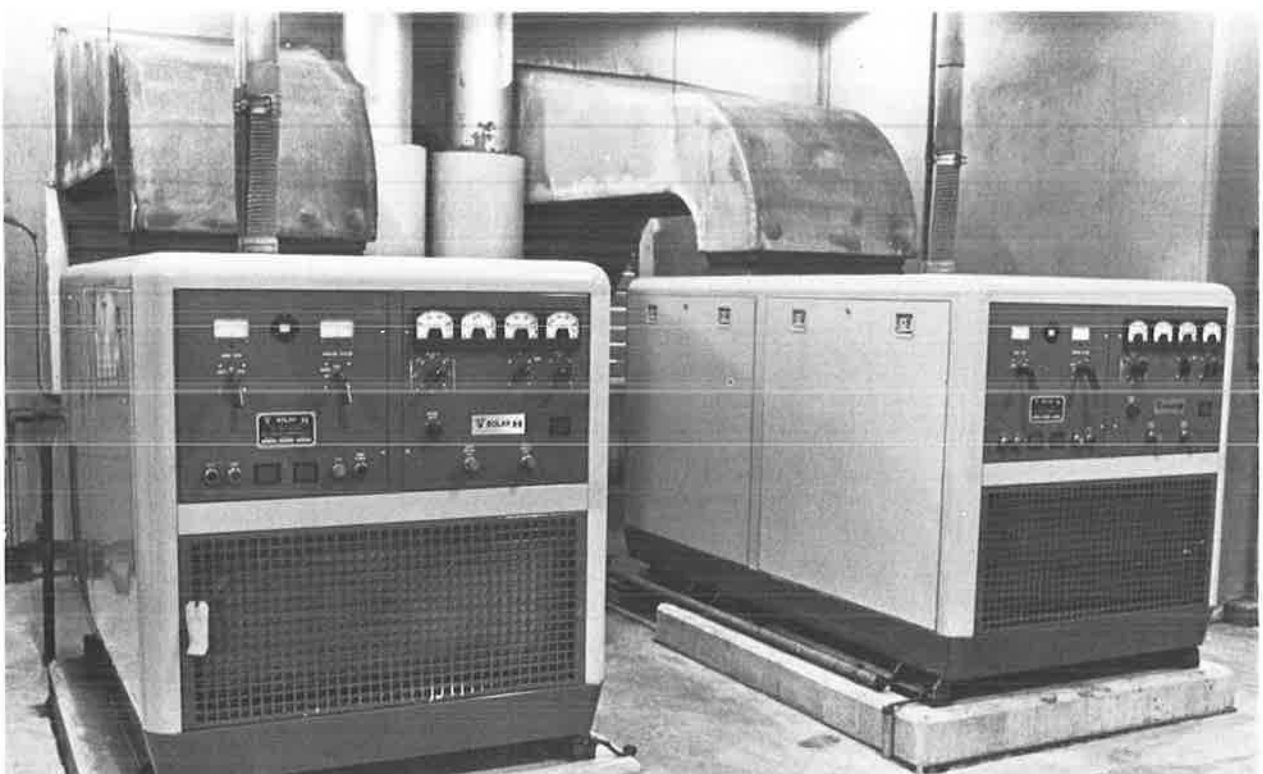


Figure 20. Standby generators (Pennsylvania Turnpike).

fan dampers. The Wallace tunnel has a 500-kVA generator powered by a natural gas engine (LP gas also can be used) that will operate most tunnel facilities; plus, until the generator starts (or if it does not start), a battery system (Fig. 21) operates one-fourth of the night lighting, the TV system, the carbon monoxide (CO) detectors, and the portal traffic signals, which are automatically turned to red. A similar system is used at the Eisenhower tunnel. At other tunnels, standby equipment includes generators with capacity to operate complete tunnel facilities (New River tunnel) or capacity to operate only lighting in the control buildings, the CO monitors, and communications gear (Holland tunnel). At all tunnels having standby equipment, that equipment starts automatically on failure of the utility source.

Standby equipment must be tested regularly to assure proper operation in an emergency. At the Brooklyn-Battery tunnel, standby generators are automatically run for 15 minutes each week; at the Caldecott tunnel they are tested monthly. The standby equipment is run weekly at the Wallace tunnel and each month a power failure is simulated and the generator run for an hour. The generators at Big Walker tunnel in Virginia are run once a week without a load and once a month with a load. The battery-powered AC generator at the Baytown-LaPorte tunnel is checked for one minute every day and the diesel generator is placed in service for a half hour four times every three weeks.

Figure 21. Emergency battery system for Wallace Tunnel. (Courtesy Alabama Highway Dept.)

CHAPTER FIVE

VENTILATION

Artificial ventilation of a tunnel may be one of three types: longitudinal, transverse, or semi-transverse (Fig. 22). With longitudinal ventilation (Fig. 22a) no ducts are used—air is pumped in (or out) at a single location and the tunnel tube itself is used as a duct. Air movement is aided by the piston action of one-way traffic flow. In the transverse method (Fig. 22b), separate ducts are used for supplying fresh air and exhausting vitiated air. The air moves transversely across the tube between fresh air and exhaust openings. For semi-transverse ventilation a single duct is used, usually for fresh air supply (Fig. 22c), but there are many variations (Figs. 22d, 22e). In each case powerful fans

(Fig. 23) are used to supply the fresh air and draw out the exhaust air.

Because semi-transverse and longitudinal ventilation systems are usually designed for one-way movement of traffic, ventilation problems may occur if two-way traffic is operated in the tunnel. Except when traffic is very light, the fans may not be able to cope with the turbulence and air surges created by two-way traffic. The result at one tunnel was extremely high carbon monoxide levels and excessive bearing and shaft wear on fans and drive equipment.

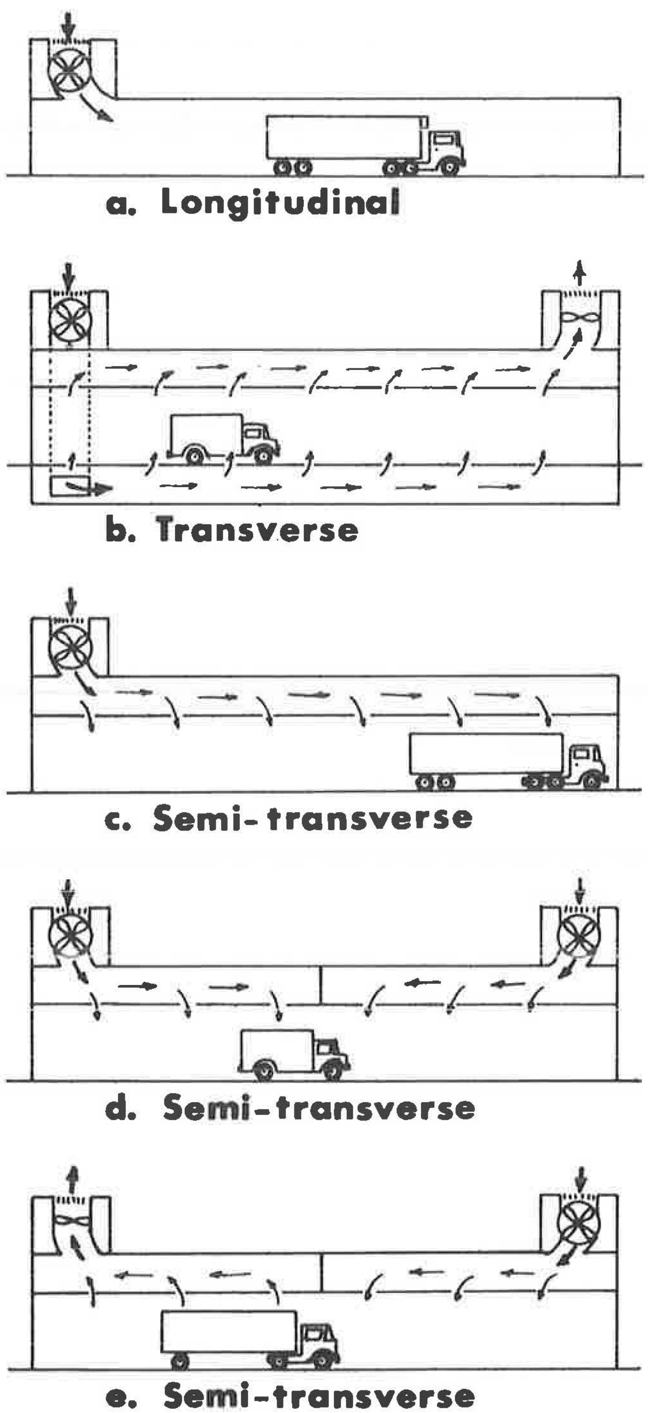


Figure 22. Ventilation types.

FAN OPERATION

The flow of fresh air into and exhaust air out of a tunnel is controlled by changing the number of fans operating and/or the speed at which they run. Although a few tunnels use single-speed fans, most tunnel fans have multispeed capability because they are driven by multispeed motors (two to four speeds are used) or by high- and low-speed motors.

At many tunnels a minimum level of ventilation is always provided and is increased as necessary. In general, fans or additional fans are turned on as monitoring equipment indicates a buildup of carbon monoxide (CO) in the tunnel. The procedure for increasing air flow may be carried out automatically or manually by an operator in the control room. An automatic sequence of fan operation triggered by rising CO levels is given in Table 1. At sequence 5 the portal traffic lights are turned red to stop traffic from entering the tunnel. As CO levels fall the sequence is reversed.

At several tunnels, the operator increases ventilation when he anticipates increased traffic, such as before morning or evening rush hours, or when a stoppage occurs. In these cases, automatic controls may be overridden. At the Brooklyn-Battery tunnel a computer is being installed that will turn on fans in anticipation of rush-hour traffic. A traffic detector and computer system at the Wallace tunnel senses traffic volumes and can increase fan speeds before the CO analyzers detect increased CO levels.

At several tunnels operation of fans is rotated so that wear will be uniform. Time meters for each fan motor at the Broadway tunnel indicate the number of hours of motor operation at each of the two speeds. A transfer switch allows the operation sequence of the fans to be interchanged to keep the operation time of each motor equal. The computer at the Brooklyn-Battery tunnel is expected to be able to keep the hours of operation of fan motors uniform.

Procedures are available at each tunnel for emergency operation of ventilation in case of fire in the tunnel. With transverse ventilation, these procedures usually require maximum ventilation in the affected section of the tunnel to eliminate smoke and gases. With semi-transverse ventilation, methods are used to convert the air supply duct to an exhaust duct. At the Fort Pitt tunnel, separate exhaust fans (normal ventilation is supply only) are started, special dampers are opened and the air supply duct becomes an exhaust duct. At the Wallace tunnel, the fans can be reversed to create an exhaust, although this will be done only at the direction of fire officials.

TABLE 1

AUTOMATIC SEQUENCING OF FANS AND FAN SPEEDS [a]

SEQUENCE	FAN NO. 1	FAN NO. 2
1	Low speed	Off
2	Low speed	Low speed
3	High speed	Off
4	High speed	High speed
5	High speed (alarm)	High speed

[a] Broadway Tunnel, San Francisco.

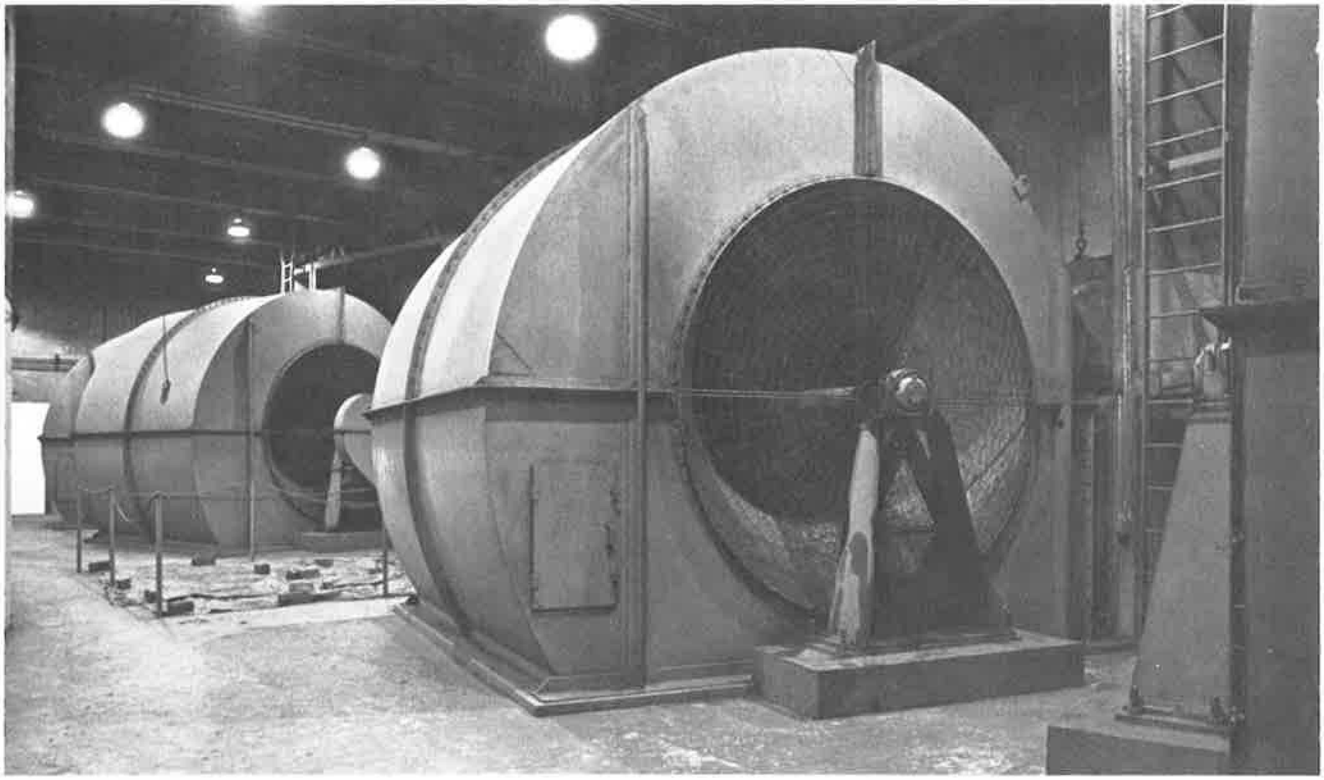


Figure 23. Ventilation fans.

At most tunnels the installed capacity of the fans is such that loss of a single fan or motor will not affect the capability to provide maximum designed air flow.

MONITORING EQUIPMENT

The condition of the air in a tunnel must be continually monitored to avoid carbon monoxide buildup. All tunnels have a system to sample, analyze, and record CO levels. The most widely used is the hopcalite analyzer (Fig. 24). Air is pumped from sampling points in the tunnel to the analyzer and the CO level is determined. This system entails a delay of 4 to 10 minutes, depending on the distance from sampling point to the analyzer. Placement of the analyzer in the tunnel has been used to reduce the delay to less than a minute. Infrared analyzers are used in a few tunnels. Regardless of the analyzer used, the CO data are transmitted to a recorder (Fig. 25) for a permanent record of time and CO levels.

In tunnels with manual ventilation control, an operator observes the CO recorder and adjusts air flow to keep CO levels within safe limits. Visual indicators (red lights) and audible alarms (bells or horns) are connected to the recorder in case the operator fails to respond to rising values of CO.

Where automatic ventilation control is used, the fresh air supply is changed automatically in accordance with the rising and falling values of CO. At several tunnels CO levels in excess of some preset maximum value will also turn the

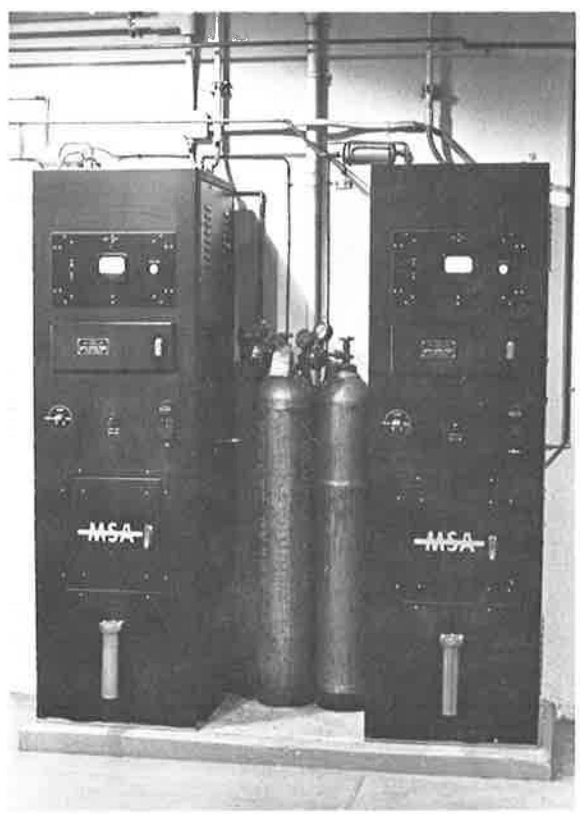


Figure 24. Carbon monoxide analyzer.

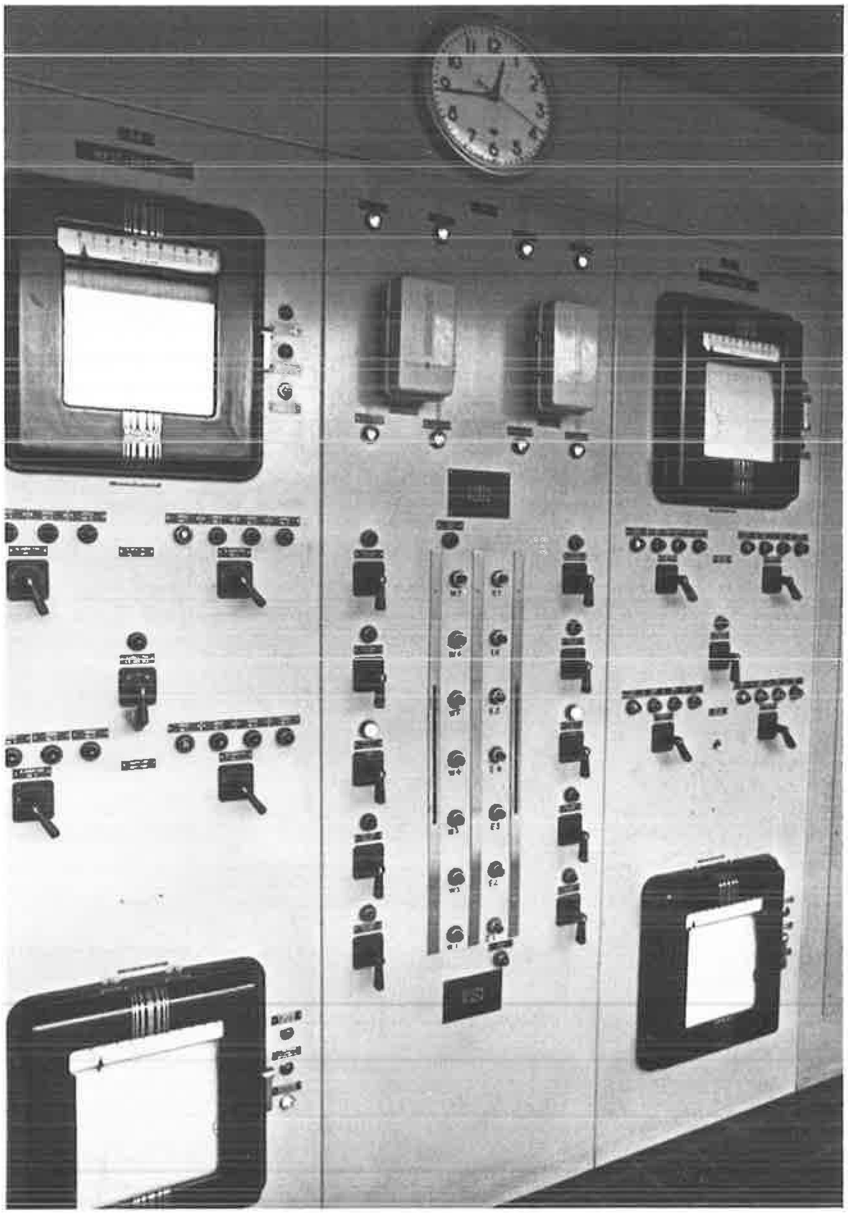


Figure 25. Control panel with CO recorders.

portal lights to red, thus stopping vehicles from entering the tunnel until the CO drops to a safe level.

Carbon monoxide analyzers and recorders are checked at least weekly and calibrated monthly. Calibration is accomplished with the use of certified cylinders of CO-free air and air with a known percentage of CO. Portable testers are sometimes used in tunnel tubes to verify correct operation of the CO monitoring system.

Because of reduced CO emissions from automobiles and sizable smoke emissions (but little CO) from diesel engines, smoke detectors have been installed at the Lincoln tunnel. When the smoke detector indicates considerable smoke in the tunnel, the ventilation is increased even though CO levels do not require additional ventilation. The smoke detectors work well but require frequent cleaning.

CHAPTER SIX

COSTS

Operation and maintenance of a highway tunnel is far more expensive than other highway facilities. However, comparison of operating and maintenance costs among tunnels is difficult. A tunnel that is long, urban, and under water has much higher costs than a short, rural, mountain tunnel. Differences in operating policies will greatly influence expenses, even for similar tunnels. For example, a policy that tolerates longer traffic delays (and thus no towing equipment is stationed at the tunnel) will result in lower costs to the tunnel agency although user costs will be higher.

Costs often are difficult to obtain. Some tunnels are maintained and operated by a highway division with other maintenance and operating responsibilities, and costs are not separated. At other tunnels one or more divisions have some responsibility for the tunnel and there is no separate cost accounting. Nonetheless, costs were obtained from 17 tunnel operators.

For comparison, costs were calculated on the basis of vehicle-miles of travel and also on the basis of lane-miles of tunnel. Neither of these methods is truly accurate because some costs, such as lighting, are independent of traffic volume and others are partially dependent on traffic. Electricity costs are given in kilowatt-hours (kWh) because the data were readily available and differences in the price of electricity are eliminated. An attempt was made to obtain labor costs in man-hours but these data were not available.

The expenses given in the tables are those for labor, parts and supplies used for traffic surveillance, operation and maintenance of ventilation, relamping, tunnel washing, and the like. Costs of toll collection and policing are not included.

The annual tunnel operating and maintenance expenses are given in Table 2. This table is based on information from 12 multilane tunnels, half of which are mountain tunnels and the other half underwater tunnels. Each tube operates one-way except when maintenance is being performed. Data from five two-lane tunnels also are given in Table 2.

These are extraordinarily high costs, especially when compared to the average costs of maintenance and traffic services for highways. Data from "Highway Statistics" * on costs (Table SF-4), and on mileage (Table SM-1) indicate a national average cost for maintenance and traffic services of about $3,200 per mile ($2,000/km) for rural primary highways and about $5,000 per mile ($3,000/km) for municipal extensions of state highway systems. However, individual states range as high as $43,000 per mile ($27,000/km) for municipal extensions. Note that these are costs per mile of highway whereas the tunnel costs are per lane-mile.

* "Highway Statistics." FHWA, U.S. Department of Transportation (1972) 216 pp.

TABLE 2

ANNUAL OPERATING AND MAINTENANCE EXPENSES FOR TUNNELS [a]

ITEM	PER 1,000 VEH-MI $	PER 1,000 VEH-MI KWH	PER LANE-MILE $	PER LANE-MILE KWH
(a) 4- AND 6-LANE TUNNELS [b]				
Range	16 to 75	123 to 287	44,000 to 434,000	426,000 to 1,438,000
Average	35	207	141,000	888,000
Median	27	228	113,000	823,000
(b) 2-LANE 2-WAY TUNNELS [c]				
Range	108 to 187	307 to 553	221,000 to 861,000	944,000 to 2,260,000
Average	148	396	494,000	1,543,000

[a] Based on 1973 cost data.
[b] Twelve tunnels.
[c] Five tunnels.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

A tunnel is the only practical solution for many situations. In other situations a tunnel may be one of the alternatives being considered. Although there has been concern with the initial costs of the various alternates, there has not been as much interest in the operating and maintenance costs. Yet, when a tunnel is opened to traffic the lights are turned on and never again turned off, and ventilation, cleaning, and other expenses begin.

If a tunnel is necessary, it should be designed with operations and maintenance in mind. Designers should be aware of the special equipment required and the problems at existing tunnels. Designers and operators should coordinate as early as possible to assure proper choice of geometrics, materials, and equipment that will minimize operating and maintenance problems and costs yet provide a design that is structurally, mechanically, electrically, and operationally efficient.

Many existing tunnels have significantly reduced traffic capacity compared to open highways. To increase capacity of future tunnels, lanes should be at least as wide as on approach roadways, shoulders should be provided where feasible, and vertical clearances should be as great as on adjacent highways to eliminate the overheight vehicle problem.

Equipment should be "off-the-shelf" insofar as possible. Replacement parts for specially built items become difficult to obtain after several years. The initial hardware package for a tunnel should include equipment (or at least provisions) for traffic surveillance and control.

Provisions for fire fighting are a part of every tunnel design. However, the problems of automatic sprinkler systems in tunnel tubes appear to outweigh the advantages and these systems should not be built into tunnels except for special applications such as in fan ducts.

The major concern with maintenance of tunnel lighting has been the replacement of burned-out lamps. More emphasis should be placed on determining the actual light level in the tunnel and then deciding what measures are needed to bring the level up to the designed level (including maintenance factor).

Signing is a continuing problem in tunnels. There is little space available for standard signs and signals and motorists frequently fail to pay attention to the signs and signals that are used within tunnels. It is recommended that at least standard colors and messages be used in tunnel signs, although more research is warranted on the most effective signing methods in tunnels.

Transportation of hazardous cargo through tunnels is a problem. Some agencies have detailed regulations on transportation of hazardous materials through their facilities and can exercise tight control. Other agencies have few or no restrictions on hazardous cargo and some have no enforcement of their regulations. As a minimum standard, the federal Motor Carrier Safety Regulations and Hazardous Materials Regulations should be followed. Because of enforcement problems and because transportation of hazardous materials on alternate routes may expose the public to more danger than in a tunnel, consideration should be given to allowing passage through tunnels on a permit basis only during specified off-peak hours.

A tunnel is an expensive facility to construct, operate, and maintain. All possible steps should be taken to minimize expenses while providing proper service to the motoring public.

APPENDIX A

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APPENDIX B

DATA FOR TUNNELS WITH ARTIFICIAL VENTILATION AND LENGTH GREATER THAN 500 FT (150 M)

State	Name and Location	Operator	Date Opened	Length Portal to Portal ft	m	Tubes	Lanes/ Tube	ADT	Vent(a)
Ala.	BANKHEAD. U.S. 90 under Mobile River; Mobile.	Ala. Highway Department	1941	3109	948	1	2	10,000	
	WALLACE. I-10 under Mobile River; Mobile.	Ala. Highway Department	1973	3000	914	2	2	22,000 (c)	S
Cal.	BROADWAY. Broadway betw. Hyde and Mason Sts.; San Francisco	City of San Francisco	1952	1616	493	2	2	28,500	L
	CALDECOTT. Cal. Route 24 at Contra Costa-Alameda Cnty. line; Oakland	Calif. Div. of Highways	1937 1965	3610 3371	1100 1027	2 1	2} 2}	100,000	T
	COLLIER. U.S. 199 near Oregon state line; Del Norte County	Calif. Div. of Highways	1963	1835	559	1	2		S
	POSEY. Cal. Route 260 under Oakland Estuary; Oakland	Calif. Div. of Highways	1928	3545	1081	1	2	24,500	T
	WEBSTER ST. Cal. Route 260 under Oakland Estuary (Companion to Posey)	Calif. Div. of Highways	1963	3350	1021	1	2	24,500	T
	LAKEWOOD BLVD. Cal. 19 under Long Beach Airport Runway; Long Beach	City of Long Beach	1958	908	277	2	3		S
	SPRING ST. Spring Street under Long Beach Airport Runway; Long Beach	City of Long Beach	1958	1080	329	2	2		S
	SECOND STREET. Second Street between Figueroa and Hill Sts.; Los Angeles	City of Los Angeles	1924	1502	458	1	4		L
	SEPULVEDA BLVD. Cal. 1 under L. A. Internat'l. Airport runway; L. A.	City of Los Angeles	1953	1908	582	2	3	54,400	T
	THIRD STREET. Third Street between Flower and Hill Sts., Los Angeles	City of Los Angeles	1901	1059	323	1	2		L
Colo.	EISENHOWER. I-70 under Continental Divide; 60 mi. W. of Denver	Colo. Dept. of Highways	1973	8941	2725	1	2	8,200	T
Conn.	WEST ROCK. Wilbur Cross Pkwy. (Route 15); New Haven	Conn. Dept. of Transportation	1949	1200	366	2	2	31,000	L
D. C.	CENTER LEG. I-95 under the Mall, Washington.	D. C. Dept. of Transportation	1973	3400	1036	2	4	58,000 (c)	T
	DUPONT CIRCLE. Connecticut Ave. under Dupont Circle; Washington	D. C. Dept. of Transportation	1950	578	176	2	2	27,000	L
	9TH STREET. 9th Street under the Mall; Washington	D. C. Dept. of Transportation	1971	1610	491	1	3	14,000	S
	12TH STREET. 12th Street under the Mall; Washington	D. C. Dept. of Transportation	1964	729	222	1	3	22,000	L

State	Name and Location	Operator	Date Opened	Length Portal to Portal ft	m	Tubes	Lanes/Tube	ADT	Vent.(a)
Fla.	NEW RIVER. U.S. 1 under New River; Fort Lauderdale	Fla. Dept. of Transportation	1960	800	244	2	2	44,000	L
H.I.	WILSON. Kalihi Valley; Honolulu	City & County of Honolulu	1960	2780	847	2	2	35,000	
La.	BELLE CHASSE. State Route 31 under Intra-coastal Waterway; Algiers	La. Dept. of Highways	1956	800	244	1	2		S
	HARVEY. Bus. U.S. 90 under Intracoastal Waterway; Harvey	La. Dept. of Highways	1957	1080	329	2	2		S
	HOUMA. State Route 3040 under Intra-coastal Waterway; Houma	La. Dept. of Highways	1961	960	293	1	2		L
Md.	BALTIMORE HARBOR. Under Patapsco River; Baltimore	Md. Dept. of Transportation	1957	7650	2332	2	2	65,500	T
Mass.	DEWEY SQUARE. John Fitzgerald Expwy. under Dewey Sq.; Boston	Mass. Dept. of Public Works	1958	2400	732	2	3	125,000	L
	CALLAHAN. U.S. 1 under Boston Inner Harbor; Boston	Mass. Turnpike Authority	1962	5070	1545	1	2	65,000	
	SUMNER. U.S. 1 under Boston Inner Harbor (Companion to Callahan)	Mass. Turnpike Authority	1934	5657	1724	1	2	65,000	T
	PRUDENTIAL CENTER. Mass. Turnpike under Prudential Center; Boston	Mass. Turnpike Authority	1964	1980	604	2	4		L
Mich.	DETROIT-WINDSOR. Under Detroit River betw. U.S. and Canada	Detroit-Canada Corporation	1930	5130	1564	1	2		T
Minn.	LOWRY HILL. I-94 under Lyndale and Hennepin Aves.; Minneapolis	Minn. Dept. of Highways	1971	1496	456	2	3	32,000 (c)	S
N. J.	G. W. BRIDGE APPROACHES. East and West tunnels on approaches to G.W. Bridge	Port Authority of N.Y. & N.J.	1962	631 547	192 167	1	2		
N. Y.	BROOKLYN-BATTERY. Under East River betw. Manhattan & Bklyn.; N.Y.C.	Triborough Bridge & Tunnel Authority	1950	9117	2779	2	2	40,000	T
	QUEENS-MIDTOWN. Under East River betw. Manhattan & Queens; N.Y.C.	Triborough Bridge & Tunnel Authority	1940 1940	6272 6414	1912 1955	1 1	2 2	60,000	T
	HOLLAND. Under Hudson Rvr. betw. N.Y.C. & Jersey City, N. J.	Port Authority of N. Y. & N. J.	1927 1927	8558 8371	2608 2551	1 1	2 2	60,000	T

State	Name and Location	Operator	Date Opened	Length Portal to Portal ft	m	Tubes	Lanes/ Tube	ADT	Vent(a)
N. Y. (Cont.)	LINCOLN. Under Hudson Rvr. betw. N.Y.C. & Weehawken, N.J.	Port Authority of N.Y. & N.J.	1937 1945 1957	8216 7482 8006	2504 2281 2440	1 1 1	2 2 2	95,000	T
	BATTERY PARK. Under Battery Park in Manhattan; New York City	New York City	1951	2400	732	2	2		S
	FIRST AVENUE. 1st Avenue under U.N. Plaza; New York City	New York City	1953	1378	420	2	2		S
	HUGH GRANT CIRCLE. I-95 under Hugh Grant Grant Circle, Bronx; N.Y.C.	New York City	1955	700	213	2	3		
	PARK AVENUE. Park Avenue between 33rd & 40th Streets; N.Y.C.	New York City	(b)	1392	424	1	2		
Ohio	LYTLE PARK. I-71 under Lytle Park; Cincinnati	City of Cincinnati	1970	850	259	2 1	3 1		L
Pa.	FORT PITT. I-79 under Mount Washington; Pittsburgh	Pa. Dept. of Transportation	1960	3600	1097	2	2	78,000	S
	LIBERTY. Under Mt. Washington betw. W. Liberty Ave. & Liberty Bridge; Pittsburgh	Pa. Dept. of Transportation	1924	5690	1734	2	2	50,000	L
	SQUIRREL HILL. I-376 under Squirrel Hill; Pittsburgh	Pa. Dept. of Transportation	1953	4225	1288	2	2	83,000	S
	ALLEGHENY. Pa. Turnpike under Allegheny Mt.; Somerset Co.	Pa. Turnpike Commission	1940 1965	6070 6070	1850 1850	1 1	2 2	18,800	S
	BLUE MOUNTAIN. Pa. Turnpike under Blue Mt.; Franklin Co.	Pa. Turnpike Commission	1940 1968	4339 4339	1323 1323	1 1	2 2	11,100	S
	LEHIGH. Pa. Turnpike, N.E. extension; Lehigh Co.	Pa. Turnpike Commission	1957	4380	1335	1	2	12,000	
	KITTATINNY. Pa. Turnpike under Kittatinny Mt.; Franklin Co.	Pa. Turnpike Commission	1940 1968	4727 4727	1441 1441	1 1	2 2	11,100	S
	TUSCARORA. Pa. Turnpike under Tuscarora Mt.; Franklin Co.	Pa. Turnpike Commission	1940 1968	5326 5326	1623 1623	1 1	2 2	11,200	S

State	Name and Location	Operator	Date Opened	Length Portal to Portal ft	m	Tubes	Lanes/Tube	ADT	Vent.(a)
Tex.	BAYTOWN-LA PORTE. SH 146 under Houston Ship Channel betw. Baytown & LaPorte	Texas Dept. of Highways	1953	3009	917	1	2	20,000	S
	WASHBURN. Federal Rd. under Houston Ship Channel betw. Pasadena and Galena Park	City of Houston	1950	2936	895	1	2		S
Va.	BIG WALKER. I-77 under Big Walker Mt.; near Wytheville	Va. Dept. of Highways & Transp.	1972	4230	1289	2	2	1,600 (c)	T
	HAMPTON ROADS. I-64 under Hampton Roads Harbor betw. Norfolk & Hampton	Va. Dept. of Highways & Transp.	1957	7479	2280	1	2	22,400	T
	DOWNTOWN. U.S. 460A under Elizabeth Rvr. betw. Norfolk & Portsmouth	Va. Dept. of Highways & Transp.	1952	3350	1021	1	2	25,000	S
	MIDTOWN. U.S. 58 under Elizabeth Rvr. betw. Norfolk & Portsmouth	Va. Dept. of Highways & Transp.	1962	4194	1278	1	2	16,000	T
	BALTIMORE CHANNEL. Under north ship channel; Chesapeake Bay	Chesapeake Bay Brdge. & Tun. Dist.	1964	5450	1661	1	2	4,000	T
	THIMBLE SHOAL CHANNEL. Under south ship channel; Chesapeake Bay	Chesapeake Bay Brdge. & Tun. Dist.	1964	5738	1749	1	2	4,000	T
Va. & W. Va.	EAST RIVER MOUNTAIN. I-77 under East River Mt. on Va.-W.Va. border	Va. Dept. of Highways & Transp.	1974	5400	1646	2	2		T
Wash.	BATTERY ST. Beneath Battery Street betw. 1st & 7th Aves.; Seattle	Wash. Dept. of Highways	1954	2140	652	2	2	23,500	T
W. Va.	WHEELING. I-70; Wheeling	W. Va. Dept. of Highways	1966	1490	454	2	2	29,000	L
	MEMORIAL. West Virginia Turnpike; Kanawha County	W. Va. Turnpike Commission	1954	2669	814	1	2		T

NOTES:

(a) Ventilation Type:
T = Transverse
S = Semi-transverse
L = Longitudinal

(b) Rehabilitated in 1973; original opening date unknown.

(c) Connecting roadways not completed.