Design for Tunnel Safety: I-90 Tunnels, Seattle

Safety issues, including the transport of hazardous cargoes, were the primary focus of the design of the mechanical and electrical systems for two highway tunnels.

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In the early 1960s, the Washington State Department of Transportation (WSDOT) began construction of the final seven-mile segment of Interstate Highway 90 that runs from Boston to downtown Seattle. The original plan included: a 14-lane freeway crossing Mercer Island with a deep cut through Mercer Island's First Hill; a new wider floating bridge (adjacent to the existing bridge which would be rehabilitated); and an open cut or multiple tunnels through Mount Baker Ridge on the Seattle side of Lake Washington.

However, in February 1971, during the preliminary stages of construction, a well organized anti-highway group obtained a "stop construction" injunction in Federal Court. The primary basis of the injunction was that the project's Environmental Impact Statement (EIS) did not adequately address the environmental impacts. Following more than eight years of environmental studies, public meetings, development of alternative concepts, and negotiations, the project's Final EIS received approval and the injunction was lifted in August 1979.

The final settlement resulted in a significantly altered design that included the use of "lidded" cut-and-cover and bored tunnels to mitigate impacts to area communities and aesthetically preserve the scenic hills. A plan for the two highway tunnels was developed for the final seven-mile segment replacing U.S. Route 10 that crossed Lake Washington and Mercer Island, and included the famous Mercer Island floating bridge crossing the lake (see Figure 1). On the west side of the lake, a pair of two-lane tunnels carried U.S. Route 10 through Mount Baker Ridge, a ridge 200 feet high along the west shore of the lake. Preliminary design started in 1982 and the tunnels were completed in 1989.

Tunnel Descriptions

The First Hill Mercer Island lid is a 2,850-foot long tunnel, consisting of three side-by-side, cut-and-cover constructed cells (see Figure 2). The tunnel has a "humped" vertical profile (see Figure 3) and its roadways are constantly curving in order to go around the foot of First Hill.

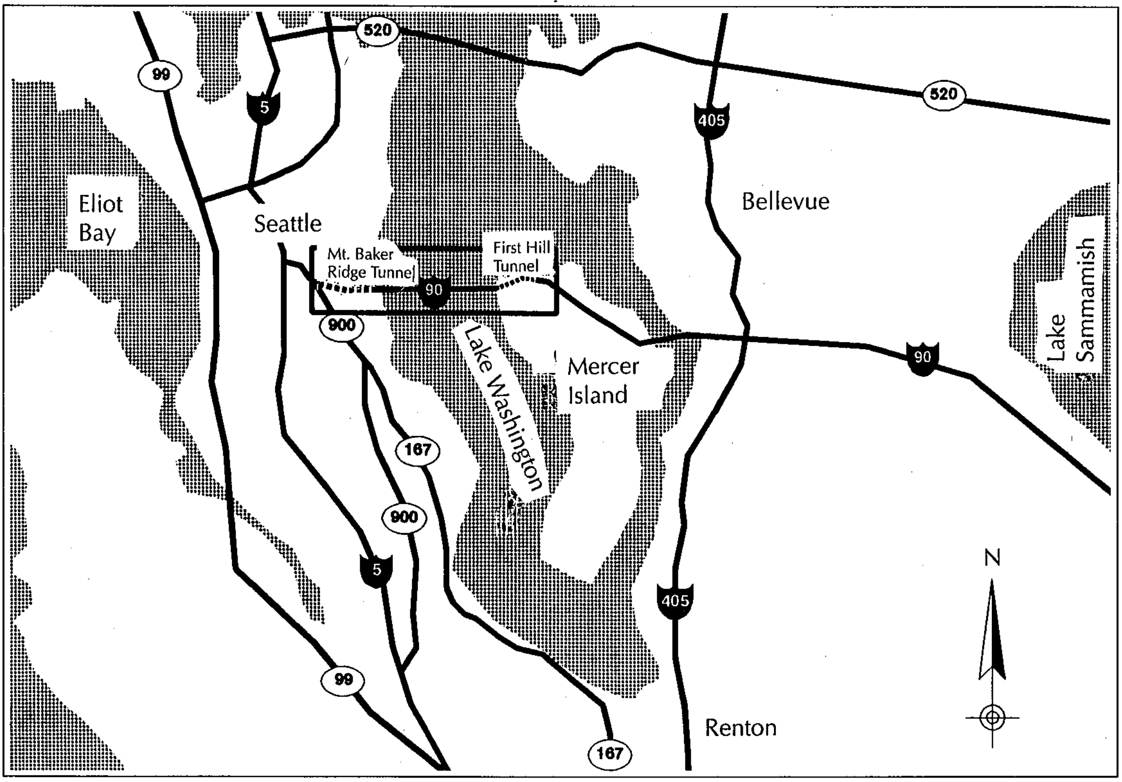

FIGURE 1. Location of the tunnel projects.

The tunnel arrangement provided considerable space above the 18-foot tunnel ceiling for the placement of supply and exhaust ducts and fan rooms. A park was constructed on the lid surface.

The Mount Baker Ridge tunnel/lid is a 3,400-foot long tunnel. It has three roadways — translating into three separate cells in the tunnel. Its westbound and center high occupancy vehicle (HOV) lanes were built while all traffic ran on the existing U.S. Route 10 tunnel roadway. After those lanes were completed, all westbound traffic used the final westbound lanes and eastbound traffic used the center

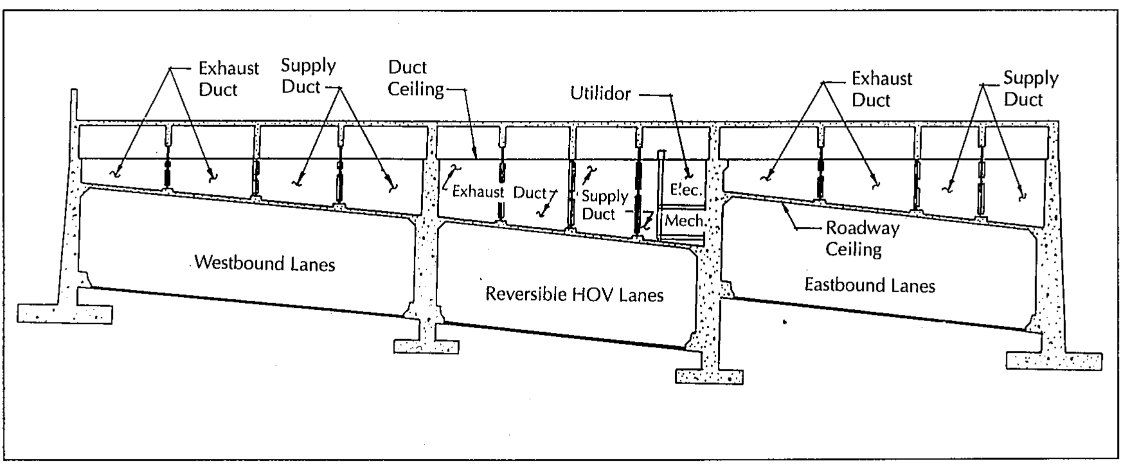

FIGURE 2. Typical section of the First Hill Mercer Island tunnel.

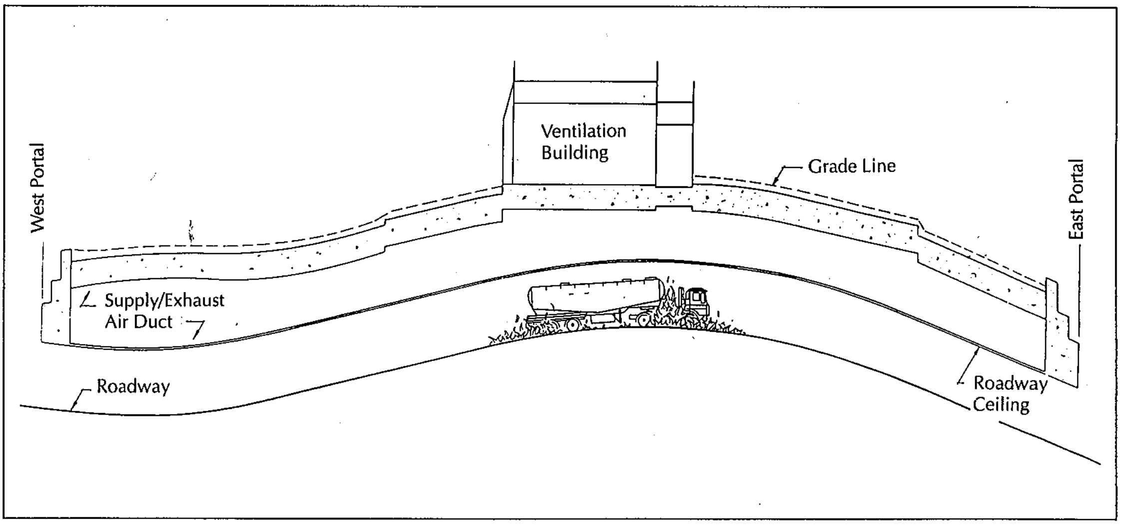

FIGURE 3. Typical profile of the First Hill Mercer Island tunnel.

roadway that was striped for three lanes. The old U.S. Route 10 roadway was left free for reconstruction into the final eastbound roadway.

Lengthwise, the Mount Baker Ridge tunnel/lid is composed of two segments. The 1,400-foot long east segment contains the westbound and center HOV roadways in a large 63-foot (inside diameter) bore, stacked with the westbound lanes in the middle, the center HOV lanes below, and a bicycle/pedestrian path above (see Figure 4). The eastbound lanes are placed in the renovated twin bore tunnels for U.S. Route 10, two lanes in one and one lane in the other.

The west segment is about 2,000 feet long and has three cut-and-cover cells, side by side, each with air ducts behind the side walls. The center HOV (going east) lanes, at about 1,000 feet into the tunnel, begin to drop and curve under the westbound lanes to enter the large bore segment.

Safety Issues

Principle safety issues for the tunnels were as follows:

- Being able to handle any incidents involving vehicles carrying hazardous cargoes that are allowed to transit both tunnels;
- Conforming to local fire department requirements for tunnel fire protection;
- Providing redundant or complementary systems for incident detection;
- Ensuring adequate and reliable fire hose valves and water supplies;
- Ensuring a continuous supply of electrical power;
- Providing access by towing and emergency vehicles that is complicated by the location of interchanges, and the roadway and bridge geometry of the highway before and after the tunnels;
- Reducing or eliminating problems regarding an east/west orientation and the "black hole" effect of entering the tunnel against a low sun and the reflection of light off the neighboring lake in the morning and evening periods;
- Providing escape exits during fire and spill emergencies or other incidents; and,
- Providing traffic control of high-speed traffic during emergency incidents in the tunnels.

Transporting hazardous cargoes, including 10,000-gallon gasoline tankers, could not be prohibited in the tunnels because of political and economic reasons as well as the lack of any satisfactory alternate routes.

The WSDOT decided that the Seattle and Mercer Island fire departments would be responsible for responding to fire emergencies in both tunnels.

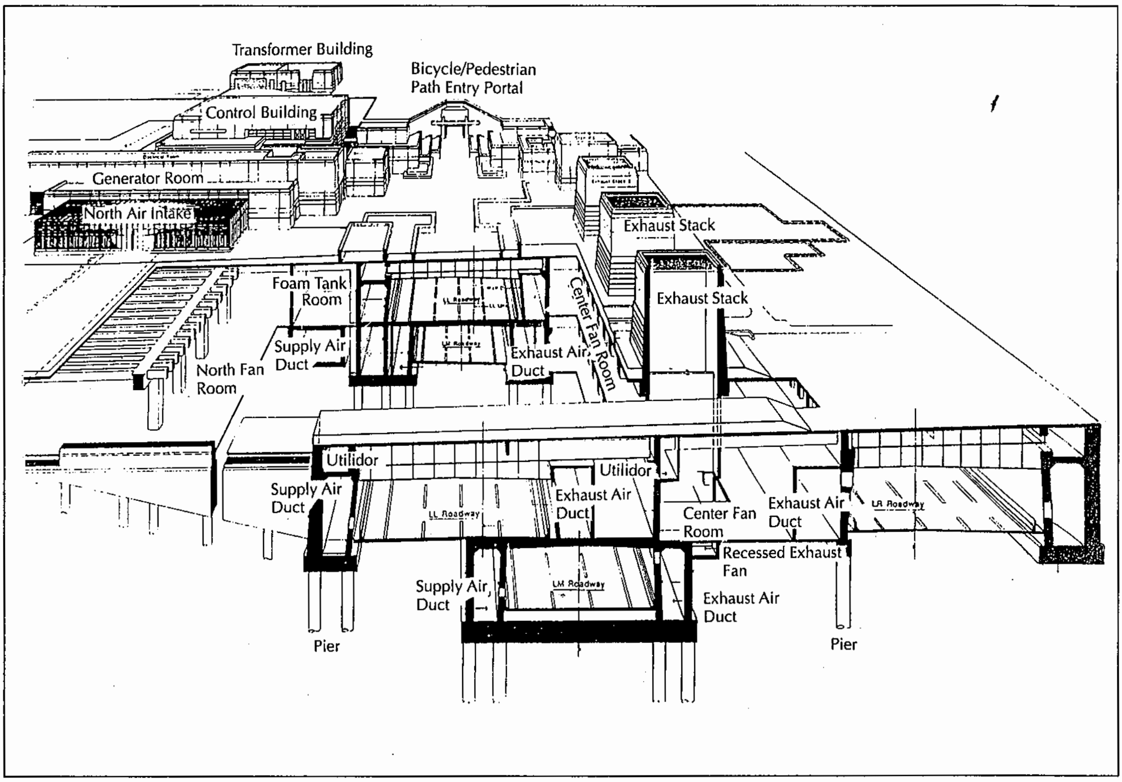

FIGURE 4. Cut-away view of the Mount Baker Ridge tunnel and associated structures.

Safety Philosophy

Safety was a paramount concern in these tunnels. The design effort focused on a two-fold approach: the creation of safety systems for incident prevention and management; and the creation of control systems for response to, as well as detection and control of, incidents. Included as a significant factor in the design of the safety systems were the safety aspects of the roadway geometry for both tunnels.

Safety Systems

The following systems were developed for incident prevention and management.

Fire Protection. The Seattle and Mercer Island fire departments required that foam sprinkler systems be installed in each tunnel where vehicles carrying hazardous cargoes would be permitted. Design concerns for the fire protection system were as follows:

- Location of sprinkler heads;
- Required foam capacity;
- Available water supply/required water capacity and pressure;
- Freeze protection of sprinkler system;
- Most effective sprinkler system for foam/water application;
- Accidental or normal foam discharge on moving traffic;
- Corrosion protection of sprinkler system; and,
- Storage and distribution of foam concentrate.

Studies using applicable computer modeling for different fire schemes (size and location of the fire in the tunnel) determined that the center HOV cells would not require sprinklers. This decision did not have an impact on normal operation; however, during the construction period when the eastbound traffic used the center HOV roadway temporarily, hazardous cargoes had to be banned.

Reasoning that discharges from sprinklers installed on walls would be blocked by large trailer trucks in the close-by lanes, it was de-

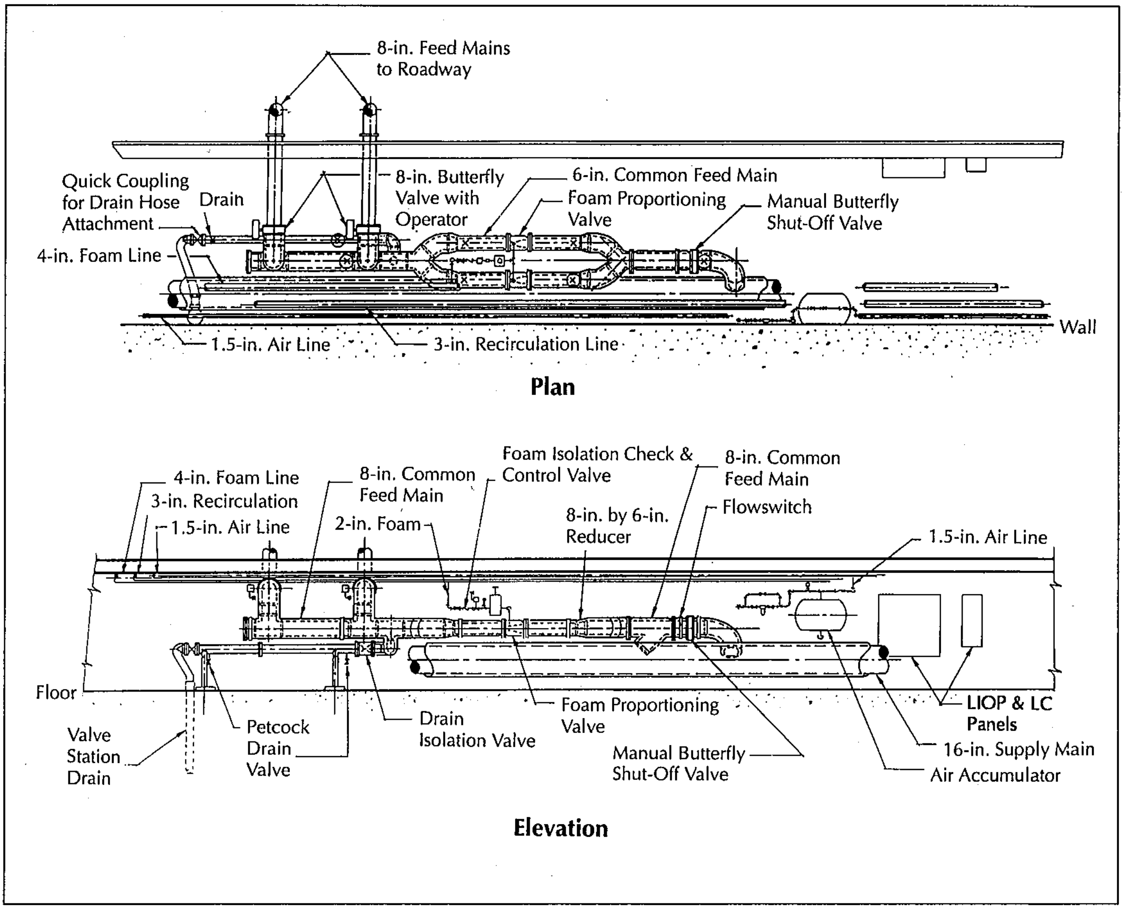

FIGURE 5. Piping arrangement for the valve stations.

cided to install sprinkler heads on the ceiling spraying downward.

To meet National Fire Protection Association (NFPA) requirements, a water flow rate of 0.16 gallons per minute (gpm) per square foot with a foam concentrate of three percent was the basis of design.

The open deluge-type sprinkler system is divided into zone arrays approximately 150 feet long (along the tunnel ceiling), spanning the width of the roadway. Open sprinkler heads spaced on a ten-foot by ten-foot grid are fed by a piping array that was designed to be pressure balanced for the particular zone. The array piping was designed for freeze protection by allowing the piping to drain through the heads after flow is stopped.

A valve station located near each zone array provides the water/foam proportion control for each zone (see Figure 5). Foam concentrate is added at this valve station through a proportioner set to provide the desired water/foam mixture percentage.

This design allows two sprinkler zones to be activated at one time without exceeding the system's water capacity from municipal water supply mains. If a fire is located in a border area between two sprinkler zones, both zones can be activated without overloading water capacity.

Each tunnel was equipped with a foam concentrate storage and pumping center that pumps the concentrate to each valve station. All control valves on both the water supply and the concentrate piping are pneumatically operated.

Fire Hydrant & Hose Valve Systems. All tunnel cells are equipped with a fire main with hydrants. Since all tunnel roadways are built on the earth (except in the Mount Baker Ridge large bore segment), wet water mains were buried under the pavement with regular-type hydrants in covered pits in the shoulder areas. Spacing, hydrants and capacities were designed in accordance with recommendations in NFPA 502.

Tunnel Roadway Drainage. Both tunnels have "humped" profiles with roadways high at the midpoint and low at the portals. Roadway drains are piped to stormwater sewers that run into Lake Washington or other environmentally sensitive receptors.

Drainage from the tunnels could be contaminated by the following:

- From tunnel interior washing (detergent, oil, filth, etc.)
- Foam sprinkler dumps
- Spill of fuels or cargoes

To prevent any of the above from flowing into the lake, at each portal the outfall drains have manually-operated valves that divert contaminated flow into holding tanks from which the contaminated water can be trucked away for proper disposal.

Ventilation. The EIS mandated a fully transverse ventilation system for the tunnels. Each roadway of each tunnel was equipped with three supply and three exhaust fans, except for the Mount Baker Ridge eastbound lanes which have six exhaust and three supply fans (totaling 39 fans for the two tunnels). Fan rooms were located at the center of each tunnel. Ducts split and parallel the roadways to each portal so that air is evenly supplied and exhausted along the total length of each roadway.

The selected intake fans are centrifugal double-width, double-inlet-type with a single motor controlled by variable frequency drives (VFDs) providing fan speeds that vary from ten percent to full speed. Exhaust fans are ducted type with inlet boxes. Fan housings are fabricated of stainless steel for anti-corrosion protection, thereby eliminating the need for constant painting. The exhaust fans are sized much larger than the supply fans to help clear the tunnel of smoke due to a fire and exhaust fumes during periods of heavy traffic.

Emergency Cabinets — "SOS Boxes." Wall niches with an emergency telephone, fire alarm pull boxes and a 20-pound dry powder type fire extinguisher were installed every 350 feet on both walls of all roadway cells, opposite one another to prevent people from crossing lanes to access the nearest cabinet. These niches were marked "SOS" and painted a distinctive color.

Communications. In the event of an incident, communications regarding the incident are of great importance. The First Hill lid and the Mount Baker Ridge tunnel/lid were equipped with such communication systems as:

- Radio rebroadcast antennas, spanning the full length of the tunnels, to allow emergency services personnel to communicate with their dispatchers; and,
- A commercial radio rebroadcast system with an override system to advise vehicle occupants of critical situations in the tunnels.

Tunnel Lighting. Lighting of a tunnel, particularly during daylight hours is an important factor in overall tunnel safety. Over the years many opinions have been expressed, papers written, and designs made for solving the problem of a motorist entering the darker interior of a tunnel from bright sunlight. Of particular concern was that motorists driving west on the floating bridge on Lake Washington approaching the Mount Baker Ridge tunnel portal would have problems with adjusting to differences in lighting because the direct afternoon sunlight from low over the Mount Baker Ridge and light reflecting off the lake shines in motorists' eyes.

A "counterbeam lighting" system was recommended for both tunnels. Counterbeam high pressure lighting employs point source controlled lighting where, in the threshold and transition zone, the luminaire directs a beam of light at a 45-degree angle towards the driver. The pavement appears bright due to its specular characteristics, thus improving contrast and visibility for motorists entering the tunnel. This method of controlling the luminaires' light distribution to increase contrast allowed a reduction in the overall lighting power consumption, initial installation and maintenance costs.

Escape Means. Both tunnels were equipped with escape exits to the surface. These exits are located in the center of each tunnel, which all roadway cells could access through cross passage.

Ease of Maintenance. The tunnel systems were designed for uncomplicated maintenance. Equipment and materials such as electrical boxes, wireways, fan housings, tunnel lighting housings and supports were made of stainless steel to decrease the need for maintenance such as painting and repair due to corrosion. Structural steel was also protected from corrosion for long-term life. To prevent corrosion in the extensive piping system, welded joint stainless steel tubing was used for all sprinkler and foam concentrate piping. Victaulic couplings and expansion joints were used throughout the water/foam concentrate distribution piping system to provide flexibility and ease of maintenance.

The structure itself was so designed that any part of the structure could be accessible for inspection via access passages in case of an earthquake. Also, any structural steel that could be exposed to excessive heat was fireproofed.

Tunnel luminaires were a custom design. Housings were designed to allow maintenance personnel to remove and replace an entire luminaire without any special tools.

Safety Aspects of Roadway Geometry

During the early design phase of the project, there was concern about the geometry of the roadways of the First Hill facility and the center roadway of the Mount Baker Ridge tunnel. As noted before, the First Hill roadways were "humped," rising in elevation to a high point at the center and downgrade to the exit portal (either way of traffic direction). At the same time, these roadways curved and were superelevated accordingly. Further complicating matters was the project architects' requirement that the side walls be tilted inward, narrower at the ceiling and wider at the roadway level.

However, vertical and horizontal curvatures were gentle enough that neither the walls nor the ceiling obstructed the driver's view of the roadway.

Well aware of the importance of tunnel roadway geometry in tunnel safety, the project designer and WSDOT carefully studied this aspect of the design of these tunnels. For the First Hill lid, the concern was the fact that neither the roadway, ceiling or walls related to the horizontal or vertical and that these visual parameters continually change as the driver proceeds through the tunnel. At First Hill, the changes are in one direction horizontally and the curvature does not reverse. Vertically, the ride is first up and then down. It was decided, after some discussion, to keep the ceiling parallel to the roadway.

The center roadway reversible HOV lanes of the Mount Baker Ridge tunnel going east drops and turns under the adjacent westbound roadway and then proceeds straight as an arrow to the east portal through the large bore segment. Realignment to the center position takes place on bridges over the lake outside the tunnel.

To evaluate these curving roadways with respect to possible driver disorientation and consequent possible safety problems, WSDOT employed a computer program that used perspective drawings from a driver's viewpoint. The drawings were then showed in rapid sequence to show how the driver's view would change as the vehicle proceeded through the tunnel. This effort convinced WSDOT that the geometry would not be a problem and would not cause driver disorientation or become a safety problem.

New Jersey safety barriers were installed against each interior tunnel wall. There were no provisions for a sidewalk, high or low, for fear that any activity by people on the sidewalk might distract motorists and cause safety problems. The 18-foot clearance allows 1.5 feet for tunnel lighting, signs, traffic lights, etc.

Tunnel Systems Control

The two tunnels have numerous systems, mostly related to safety and/or fire protection, that require a control mechanism for optimum operation. The size of these systems, as well as the amount of information coming from them, dictated that the control system be electronic based.

In addition, each tunnel needs to be controlled from a centralized location. WSDOT decided that around-the-clock staffing of a control room in each tunnel would be too costly. Instead, it was determined that both tunnels would be controlled from consoles located in a freeway control center called the Traffic Systems and Management Center (TSMC). Personnel at the TSMC could "double-up" and tend both tunnel control consoles, as well as the freeway controls.

The computer control system is interactive — each system to be controlled is translated into a schematic that includes real-time indicators of the system's current status. This information can be called up on the computer's video monitor by use of a menu. This diagram changes as the system responds to commands from the operator or other sensors.

There are many separate subsystems involved in controlling the Seattle and Mercer Island tunnels. These subsystems are designed to provide monitoring and control functions for tunnel lighting, traffic control, ventilation, communications and power distribution. Each subsystem is part of the total Supervisory Control and Data Acquisition (SCADA) system that controls the tunnel. This system uses modern techniques of distributed control to dramatically increase system reliability by eliminating system interruptions due to single point failures.

The control systems are electronic and operate using analog signals, discrete (voltage level) signals and digital signals. Analog signals are produced by sensors measuring light intensity, carbon monoxide, voltage, current, power, fan speed and various other parameters. Most of these data are available through the tunnel computer system.

Programmable Logic Controllers (PLCs). The SCADA system provides monitoring and control capabilities of the tunnel operating parameters. Analog and discrete values are first measured by a subsystem such as a programmable logic controller (PLC). The PLC passes information to and from the tunnel computer over a high-level communications network (digital signal), and from there information is transmitted to the TSMC through a fiber optics network.

A failure at the TSMC or in the fiber optics line will not require tunnel closure. Likewise, tunnel computer failure does not require tunnel closure because locally distributed PLC control systems can operate independently. If an individual PLC system or component should fail, a redundant or parallel PLC (operating parallel systems within the tunnel) continues to operate the tunnel in a safe and orderly manner. In the event of multiple subsystem control failures, critical items, such as lighting and ventilation, are manually controlled in the local equipment location.

The PLCs are stand-alone subsystems and normally perform control functions based on their inputs from field sensors. They also accept inputs from the tunnel computer system regarding new control parameters or setpoints. The PLCs communicate directly with each other as well as with the tunnel computer.

Due to the safety requirements of monitoring and controlling a highway tunnel, a highly reliable information acquisition and control system with backup capabilities is required. Various means are used to obtain the desired reliability, including redundancy of sensors, standby equipment, distributed control, etc. Each tunnel has a distributed control system with five PLCs. Functional control of similar systems such as lighting, traffic signal heads, and ventilation are divided among four of the PLCs. The fifth PLC has a redundant processor and controls the substations, switchgear and standby generators where control cannot be easily divided into two separate, independent systems.

Because of the substantial length of the tunnels, a distributed digital control system with a local input-output panel (LIOP) at each valve station was selected. Another LIOP in the foam room activates foam concentrate pumps and automatically operates recirculating freeze protection. All LIOPs are supervised by a central processing unit in the control console.

Tunnel Computer System. Each tunnel is equipped with a host mini-computer operating primarily on data supplied by the operator, the PLCs and other remote subsystems. It is used to supervise the operation of the PLCs and make setpoint control changes as determined by the operator. The computer system also handles data gathering and historical files, alarm/status logging and report generation.

Inputs to the tunnel computer include the PLCs, traffic data stations, fire system, essential services and inputs from the TSMC remote control system. All inputs and outputs are available for display on a color video monitor and are accessible by operator request.

Environmental Control Panel. A separate environmental control panel is located in the control room with limited monitoring and control capabilities for the tunnel. The panel has two purposes:

- To generate a status report of tunnel operating conditions for personnel — without requiring operational knowledge of the computer system; and,
- To provide control of critical functions in the event of system control failures or during maintenance work periods on various control equipment.

The environmental control panel alone is not intended for long-term control of the tunnel.

Fire Protection. Upon detection of a fire, the computer control system increases exhaust ventilation to 100 percent (100 cubic feet per minute per lane foot) and maintains supply at 20 percent in the effected vehicular zone. Adjacent zones operate normally. In addition, tunnel closed signs come on at each portal, traffic signals upstream go to red and downstream stay green, and the tunnel lights are set to maximum brightness. These responses are programmed; however, the control room operator can change them if desired by the local fire departments or others.

The activation of a sprinkler zone is accomplished through a computer-based control that automatically activates a particular zone upon signal from a ceiling-mounted fire detector located within that particular zone. To give the control room operator time to investigate the seriousness of the fire, traffic flow and other conditions, there is a 30 to 90 second delay after the alarm sounds before the automatic response is actuated. The operator may leave the system in the auto mode and let the countdown end at the initiation of foam. However, the system also allows manual selection of one of following three alternative options:

- Abort/Reset: Sets the countdown back to seconds or resets the foam system completely if the detectors are out of alarm.
- Dump: Immediately opens the valve in the first two zones that detected an alarm.
- Silence: Continues the countdown but shuts off the alarm horn.

A separate graphic display of the tunnel's fire situation with the manual option is also located in the control room. This independent manual panel with the ability to intervene in the automatic sequence also helps to manage another problem — a blinded operator that can occur during a serious fire. For example, the detectors may report and then melt for hundreds of feet. In auto mode, the system only dumps foam on the first two zones to report a fire. In the manual mode, the operator (or the fire department) can follow the fire as long as the foam and visual observation last or communication is maintained between the fire area and the control center.

The delay period with manual response override is important with regard to SOS callbox alarms. If the door on the fire extinguisher box is opened, a door switch sounds an alarm in the control room. The SOS box location is also indicated on the console, as is the video camera in which the particular SOS box appears. Emergency telephones automatically dial 911, the control room of that particular tunnel is notified, and the tunnel control room operator can listen in. The purpose of this alarm and indicator is to:

- Inform the operator that someone needs an extinguisher to put out a fire; or,
- Someone is stealing the extinguisher.

In the latter case, the operator can abort an obvious false alarm. In the former case, the operator can judge the level of response appropriate to the incident.

Ventilation Fans. Fan speeds are controlled by PLC logic and are normally operated on a time-of-day schedule based on traffic loads with an automatic speed increase if carbon monoxide levels rise above accepted limits.

Video Control. Visual monitoring is required to detect incidents in the tunnel that are not alarmed by the fire detection, emergency telephone or incident detection systems. An attentive operator watching the video monitors may locate an incident before the incident detection system can be activated. The operator could then initiate safety or corrective actions at the earliest possible time. In the event an incident is visually detected, the operator is able to manually control a certain camera's pan, tilt and zoom (PTZ) function to visually determine the severity of the incident before taking appropriate action.

Visual monitoring of the tunnel is accomplished by approximately 30 video cameras. All cameras are monitored simultaneously on five video monitors mounted above the operator's console. These monitors use split/composite screens to present video from multiple cameras on a single monitor. One monitor is devoted to each portal and one monitor is devoted to each directional cell (eastbound, center HOV and westbound). Video recording occurs on all screens displayed at the control console by five independent videocassette recorders. These units normally run in an elapsed time recording mode.

Approximately half of these cameras are fixed and the other half have PTZ capability (in a tunnel, roughly every other camera has PTZ function). PTZ control is possible by manual operation of the console and/or automatic preset positioning. In manual mode, the operator can select any of the PTZ cameras and control these functions through the tunnel computer keyboard. Remote control of the video system from the TSMC is processed through the tunnel computer.

Carbon Monoxide (CO) Monitoring. Each traffic cell has three to four carbon monoxide detectors monitored by the tunnel control system. Included with each monitor are two alarm contacts (warning and alarm) and one trouble alarm. Carbon monoxide values are available for display on the host computer's video monitor, environmental control panel and carbon monoxide equipment rack. If the carbon monoxide concentration of an area within a traffic cell should exceed 125 parts per million (ppm), the normal fan speed control is overridden and the supply and exhaust fans for the cell are increased to maximum speeds. These settings are maintained until the carbon monoxide level decreases below 90 ppm at which time the normal control resumes operation. This occurrence causes an alarm to be generated and displayed on various tunnel control systems along with a printout of the incident. A trouble alarm from a carbon monoxide monitor is displayed on the tunnel computer monitor. A faulty sensor causing false alarms can be inhibited by the operator.

Power Loss. In the event that a power failure occurs on both of the incoming utility lines, a standby generator system is activated. This system is sized to provide an adequate power supply to operate the ventilation fans at reduced speeds. Upon power loss, the VFDs will trip, thus cutting off all power to the fan motors. Once standby generators are on line, the PLC will generate a "reset" and "start" signal to the VFDs that restarts certain fans according to other tunnel variables.

The loss of both tunnel utility feeders would also result in extinguishing all lights in the tunnel except for the emergency lights. The emergency lighting panels are provided with uninterruptible power supplies (UPSs) to insure continuous operation in case of power failure. This power loss automatically initiates the start and synchronization of the generators. Once generator power is available through the UPSs, the night-time, day-time, and Step 1 (normal portal brightest on an overcast day) lights are activated. Maximum tunnel lighting on standby generator power is Step 1.

Tunnel Cell Fire. Fires within the tunnel are monitored by the fire control system that operates independently of the tunnel computer system. It provides fire alarm and location information to the tunnel computer and also generates a fire alarm input to the ventilation fan PLCs. The tunnel computer and operator may then decide on proper signal head and sign control or rely on the automatic settings as mentioned previously. Backup controls are available on the environmental control panel if the tunnel computer fails.

When the emergency is cleared, the operator will reset the fire alarm signal and the PLC logic will automatically return the fan speed control to normal.

Manual Operation. As mentioned above, each fan is capable of being operated under manual control, independent of other fans. This control may come from the tunnel control console operator, the environmental control panel or from the TSMC. Fans may also be controlled locally from their individual VFDs. Lockout for maintenance purposes is possible locally at the fans.

Traffic Control. Traffic signal heads, neon portal signs and variable message signs (VMSs) are used to alert traffic to maintenance work or lane obstructions in the tunnel. Critical incidents requiring tunnel cell closure are handled by automatic or manual control from the tunnel control console.

A neon portal sign is located at each tunnel roadway entrance to inform motorists of an individual tunnel roadway closure. The sign can be manually activated by operator input at the computer. When activated, the sign flashes TUNNEL CLOSED followed by DO NOT ENTER. The neon portal signs are automatically activated by the PLC upon a signal from the fire system.

Upon initiation of a signal head lighting sequence in response to a tunnel fire in a given cell, all signal heads in the direction of upstream traffic simultaneously turn to a steady amber. After five seconds of steady amber, the neon portal signal are activated to announce tunnel closure, simultaneously with all upstream signal heads turning red. All signal heads downstream of the incident area remain de-energized. The control operator is able to manually override the PLC signal head logic from the tunnel control console or the TSMC. After the emergency situation is resolved, the operator can manually turn signal heads to green and the signals automatically return to the normal "off" condition in 30 seconds.

During normal operation, the VMSs are monitored and controlled by an operator in the tunnel control room through the VMS central controller. Capabilities available through this mode of control include:

- Creating and storing messages on the VMS central controller hard disk;
- Retrieving stored messages from the disk for review or modification;
- Initiating display of messages on the VMS signs;
- Causing messages to flash and controlling the yellow flashing beacons on the VMS signs;
- Viewing the current status of each sign including what message is currently being displayed;
- Scheduling messages for display on a time-of-day, day-of-week basis; and,
- Requesting a failure report for all signs in the system.

Additionally, the operator may view the status of the signs through the tunnel computer console. Backup control of the VMSs is available through the tunnel computer console in the event of failure of the VMS central controller.

Traffic Data Stations. Traffic data stations located within the tunnel cells and at ramp entrances monitor traffic conditions by accumulating traffic counts, and computing average speeds and occupancy. These data are sent to the tunnel computer every 20 seconds. The tunnel operator/TSMC may then access this information through the console and through daily reports. Incident algorithms, executing periodically on the tunnel computer, alert the operator when the relative traffic measures reported by adjacent traffic data stations suggest the presence of an incident. These algorithms are not able to detect all incidents, but can give some indications during heavy traffic periods. Neither the traffic data stations nor the incident algorithms control traffic lights within the tunnel.

In addition, a system of high-frequency induction loops on the roadway are used to detect vehicles magnetically. The operator can use the video camera system to monitor these roadway loops so that the control room can detect anomalies in traffic flow for their investigation.

Light Monitoring. Threshold, transition and interior zone luminaires are controlled in such a manner that the light levels within the tunnel can be varied in intensity by steps to suit outside conditions (for example, bright sun, time of day, cloudiness, darkness, etc.). Control is effected by outside photo cells sensing ambient light levels. Photo cells are also included inside the tunnel to sense overall interior light levels. This arrangement allows lights to be switched "off" when lamps are new and the tunnel surfaces are clean. As the surfaces get dirty and the lamp output reduces with age, lights can be turned "on" to compensate for this loss and thus maintain interior design levels. This type of control is energy efficient lighting installation since it does not overlight the tunnel interior.

Conclusions

The Seattle tunnels were designed with safety in mind — based on the creed "Prevention, Detection and Control/Response."

Prevention. Roadway geometry was carefully designed to conform to safe highway standards. Tunnel lighting design emphasized enhanced visibility for drivers as well as economy in construction maintenance and operating costs. A UPS system prevents a total blackout of tunnel lighting if power fails. Traffic lights inside the tunnel and VMSs outside were provided to stop traffic if an emergency occurs in the tunnel and to warn drivers approaching the tunnel of any problems. And, while hazardous cargoes could not be prohibited, systems to detect and control fires were installed.

Detection. The project's prime device for detection is a video monitoring system with PTZ capability and a control panel (designed for ease of use by the operator). Ceiling-mounted fire detectors tied directly into computer system automatically activate fire control systems. SOS boxes installed on each tunnel wall every 350 feet — complete with emergency telephone, fire pull and fire extinguisher — aid in incident detection. Two-way radio antennae were included for emergency vehicles to communicate with their headquarters, each other and the tunnel control room. Roadway loops spaced at 600 feet in lane are tied to an algorithm in the computer program designed to warn the operator of a stoppage or other anomaly in traffic flow.

Control/Response. A control room equipped with a computer provides an operator with the current status of all safety systems and with the ability to monitor and control all systems for emergency response. The tunnels' zoned sprinkler system automatically (with manual override) responds to fires. SOS boxes with fire extinguishers can be used by tunnel patrons. Carbon monoxide sensors warn the control room of excessive levels and automatically increase ventilation to provide more air.

The integrated system requires only one operator who oversees tunnel ventilation fans, the video monitoring system, fire pull boxes, heat detectors, the automatic/manual foam sprinkler system and the roadway loops to monitor traffic. While the tunnel safety system can function automatically to facilitate incident management, an alert and well-trained control room operator, capable of good judgment in critical emergencies, is still necessary. It is incumbent upon the tunnel manager to provide this type of personnel and to conduct exercises and training on a regular basis, where an emergency is simulated and all aspects of response personnel (police, fire, rescue) and equipment are involved.

Using state-of-the-art tunnel technology, the First Hill lid and the Mount Baker Ridge tunnel/lid have been equipped with the most modern and technologically advanced mechanical and electrical safety systems available today.

ACKNOWLEDGMENTS — *Sverdrup Corp. was project designer. FENCO Engineers of Toronto, Canada, designed the lighting system for both tunnels. A DEC Microvax serves as the host computer.*

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