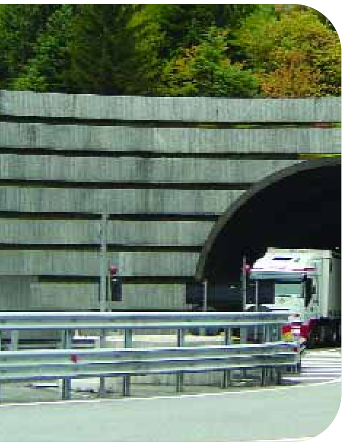
INTERNATIONAL
TECHNOLOGY
SCANNING PROGRAM

Underground Transportation Systems in Europe:

Safety, Operations, and Emergency Response



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IN COOPERATION WITH:

American Association of State Highway and Transportation Officials

National Cooperative Highway Research Program

June 2006

N O T I C E

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Technical Report Documentation Page

1. Report No. FHWA-PL-06-016	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response		5. Report Date June 2006
7. Author(s) Steven Ernst, Mahendra Patel, Harry Capers, Donald Dwyer, Chris Hawkins, Gary Steven Jakovich, Wayne Lupton, Tom Margro, Mary Lou Ralls, Jesus Rohena, Mike Swanson		6. Performing Organization Code 8. Performing Organization Report No.
9. Performing Organization Name and Address American Trade Initiatives P.O. Box 8228 Alexandria, VA 22306-8228		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTFH61-99-C-005
12. Sponsoring Agency Name and Address Office of International Programs Office of Policy Federal Highway Administration U.S. Department of Transportation American Association of State Highway and Transportation Officials National Cooperative Highway Research Program		13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes
FHWA COTR: Hana Maier, Office of International Programs

16. Abstract

The United States has limited guidelines, standards, and specifications related to safety, operations, and emergency response in underground transportation systems. The Federal Highway Administration, American Association of State Highway and Transportation Officials, and National Cooperative Highway Research Program sponsored a scanning study of equipment, systems, and procedures used in tunnels in Austria, Denmark, France, Germany, Italy, Norway, the Netherlands, Sweden, and Switzerland.

The scan team learned that Europeans are conducting research to develop innovative design and emergency management plans that consider how people react in tunnel emergencies. Because motorist behavior is unpredictable in tunnel incidents, Europeans make instructions for drivers, passengers, and tunnel operators as straightforward as possible to reduce required decisionmaking.

The team's recommendations for U.S. implementation include conducting research on tunnel emergency management that includes human factors, developing tunnel design criteria that promote optimal driver performance during incidents, developing more effective visual, audible, and tactile signs for escape routes, and using a risk-management approach to tunnel safety inspection and maintenance.

17. Key Words		18. Distribution Statement	
Emergency response, incident management, maintenance, safety, tunnel, underground transportation system		No restrictions. This document is available to the public from the: Office of International Programs, FHWA-HPIP, Room 3325, U.S. Department of Transportation, Washington, DC 20590 *international@fhwa.dot.gov* *www.international.fhwa.dot.gov*	
19. Security Classify. (of this report)	20. Security Classify. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	64	Free

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

The success of this scan was a result of the knowledge and experience shared by representatives of the host transportation agencies, researchers, associations, and private firms during the scan meetings. Scan team members thank their hosts for their gracious hospitality and for taking the time from their busy schedules to meet and discuss the latest technological developments in their countries. Each country provided information that expanded the knowledge of scan team members, and team members look forward to continued interaction and partnership with the hosts in the advancement of safety, operations, and emergency response in underground transportation systems.

The scan team also thanks the Federal Highway Administration (FHWA), the FHWA Office of International Programs, the American Association of State Highway and Transportation Officials, and the National Cooperative Highway Research Program for their leadership and support of the scan.

Underground Transportation Systems in Europe:

Safety, Operations, and Emergency Response

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June 2006

International Technology Scanning Program

The International Technology Scanning Program, sponsored by the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the National Cooperative Highway Research Program (NCHRP), accesses and evaluates innovative foreign technologies and practices that could significantly benefit U.S. highway transportation systems. This approach allows for advanced technology to be adapted and put into practice much more efficiently without spending scarce research funds to re-create advances already developed by other countries.

FHWA and AASHTO, with recommendations from NCHRP, jointly determine priority topics for teams of U.S. experts to study. Teams in the specific areas being investigated are formed and sent to countries where significant advances and innovations have been made in technology, management practices, organizational structure, program delivery, and financing. Scan teams usually include representatives from FHWA, State departments of transportation, local governments, transportation trade and research groups, the private sector, and academia.

After a scan is completed, team members evaluate findings and develop comprehensive reports, including recommendations for further research and pilot projects to verify the value of adapting innovations for U.S. use. Scan reports, as well as the results of pilot programs and research, are circulated throughout the country to State and local transportation officials and the private sector. Since 1990, approximately 70 international scans have been organized on topics such as pavements, bridge construction and maintenance, contracting, intermodal transport, organizational management, winter road maintenance, safety, intelligent transportation systems, planning, and policy.

The International Technology Scanning Program has resulted in significant improvements and savings in road program technologies and practices throughout the United States. In some cases, scan studies have facilitated joint research and technology-sharing projects with international counterparts, further conserving resources and advancing the state of the art. Scan studies have also exposed transportation professionals to remarkable advancements and inspired implementation of hundreds of innovations. The result: large savings of research dollars and time, as well as significant improvements in the Nation's transportation system.

Scan reports can be obtained through FHWA free of charge by e-mailing *international@fhwa.fhwa.dot.gov.* Scan reports are also available electronically and can be accessed on the FHWA Office of International Programs Web site at *www.international.fhwa.dot.gov.*

International Technology Scan Reports

Safety

- *Safety Applications of Intelligent Transportation Systems in Europe and Japan* (2006)
- *Traffic Incident Response Practices in Europe* (2006)
- *Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response (2006)*
- *Roadway Human Factors and Behavioral Safety in Europe* (2005)
- *Traffic Safety Information Systems in Europe and Australia* (2004)
- *Signalized Intersection Safety in Europe* (2003)
- *Managing and Organizing Comprehensive Highway Safety in Europe* (2003)
- *European Road Lighting Technologies* (2001)
- *Commercial Vehicle Safety Technology and Practice in Europe* (2000)
- *Methods and Procedures to Reduce Motorist Delays in European Work Zones* (2000)
- *Innovative Traffic Control Technology and Practice in Europe* (1999)
- *Road Safety Audits—Final Report and Case Studies* (1997)
- *Speed Management and Enforcement Technology: Europe and Australia* (1996)
- *Safety Management Practices in Japan, Australia, and New Zealand* (1995)
- *Pedestrian and Bicycle Safety in England, Germany, and the Netherlands* (1994)

Planning and Environment

- *Managing Travel Demand: Applying European Perspectives to U.S. Practice (2006)*
- *Transportation Asset Management in Australia, Canada, England, and New Zealand* (2005)
- *Transportation Performance Measures in Australia, Canada, Japan, and New Zealand* (2004)
- *European Right-of-Way and Utilities Best Practices* (2002)
- *Geometric Design Practices for European Roads* (2002)
- *Wildlife Habitat Connectivity Across European Highways* (2002)
- *Sustainable Transportation Practices in Europe* (2001)
- *Recycled Materials in European Highway Environments* (1999)
- *European Intermodal Programs: Planning, Policy, and Technology* (1999)
- *National Travel Surveys* (1994)

Policy and Information

- *European Practices in Transportation Workforce Development* (2003)
- *Intelligent Transportation Systems and Winter Operations in Japan* (2003)
- *Emerging Models for Delivering Transportation Programs and Services* (1999)
- *National Travel Surveys* (1994)
- *Acquiring Highway Transportation Information from Abroad* (1994)
- *International Guide to Highway Transportation Information* (1994)
- *International Contract Administration Techniques for Quality Enhancement* (1994)
- *European Intermodal Programs: Planning, Policy, and Technology* (1994)

Operations

- *Managing Travel Demand: Applying European Perspectives to U.S. Practice (2006)*
- *Traffic Incident Response Practices in Europe* (2006)
- *Underground Transportation Systems in Europe: Safety, Operations, and Emergency Response (2006)*
- *Superior Materials, Advanced Test Methods, and Specifications in Europe* (2004)
- *Freight Transportation: The Latin American Market* (2003)
- *Meeting 21st Century Challenges of System Performance Through Better Operations* (2003)
- *Traveler Information Systems in Europe* (2003)
- *Freight Transportation: The European Market* (2002)
- *European Road Lighting Technologies* (2001)
- *Methods and Procedures to Reduce Motorist Delays in European Work Zones* (2000)
- *Innovative Traffic Control Technology and Practice in Europe* (1999)
- *European Winter Service Technology* (1998)
- *Traffic Management and Traveler Information Systems* (1997)
- *European Traffic Monitoring* (1997)
- *Highway/Commercial Vehicle Interaction* (1996)
- *Winter Maintenance Technology and Practices—Learning from Abroad* (1995)
- *Advanced Transportation Technology* (1994)
- *Snowbreak Forest Book—Highway Snowstorm Countermeasure Manual (translated from Japanese)* (1990)

All publications are available on the Internet at:

www.international.fhwa.dot.gov

Infrastructure—General

- *Construction Management Practices in Canada and Europe* (2005)
- *European Practices in Transportation Workforce Development* (2003)
- *Contract Administration: Technology and Practice in Europe* (2002)
- *European Road Lighting Technologies* (2001)
- *Geometric Design Practices for European Roads* (2001)
- *Geotechnical Engineering Practices in Canada and Europe* (1999)
- *Geotechnology—Soil Nailing* (1993)

Infrastructure—Pavements

- *Quiet Pavement Systems in Europe* (2005)
- *Pavement Preservation Technology in France, South Africa, and Australia* (2003)
- *Recycled Materials In European Highway Environments* (1999)
- *South African Pavement and Other Highway Technologies and Practices* (1997)
- *Highway/Commercial Vehicle Interaction* (1996)
- *European Concrete Highways* (1992)
- *European Asphalt Technology* (1990)

Infrastructure—Bridges

- *Prefabricated Bridge Elements and Systems in Japan and Europe* (2005)
- *Bridge Preservation and Maintenance in Europe and South Africa* (2005)
- *Performance of Concrete Segmental and Cable-Stayed Bridges in Europe* (2001)
- *Steel Bridge Fabrication Technologies in Europe and Japan* (2001)
- *European Practices for Bridge Scour and Stream Instability Countermeasures* (1999)
- *Advanced Composites in Bridges in Europe and Japan* (1997)
- *Asian Bridge Structures* (1997)
- *Bridge Maintenance Coatings* (1997)
- *Northumberland Strait Crossing Project* (1996)
- *European Bridge Structures* (1995)

Acronyms

AASHTO American Association of State Highway and Transportation Officials

APTA American Public Transportation Association

CCTV Closed-circuit television

CETU Tunnel Study Centre at the French Ministry of Transport, Equipment, Tourism, and Sea

CFD Computational fluid dynamics

CO Carbon monoxide

DOT Department of transportation

EU European Union

FHWA Federal Highway Administration

FM Frequency modulation

HF High-frequency

HSCOBS Highway Subcommittee on Bridges and Structures

LED Light-emitting diode

LPG Liquid propane gas

L-surF Design Study for a Large-Scale Underground Research Facility on Safety and Security

LTDS Linear temperature detection system

MTTF Mean time to failure

MW Megawatt (energy release rate of a fire)

NCHRP National Cooperative Highway Research Program

NFPA National Fire Protection Association

NO Nitric oxide

NOK Norwegian kronor

PIARC World Road Association (previously the Permanent International Association of Roadways Congress)

SEK Swedish kronor

SINTEF Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology

SINTEF NBL Norwegian Fire Research Laboratory

SP Swedish National Testing and Research Institute

STUVA German Research Association for Underground Transportation Facilities

T–20 AASHTO HSCOBS Technical Committee for Tunnels

TBM Tunnel boring machine

TNO Netherlands Organization for Applied Scientific Research

TRB Transportation Research Board

UPTUN Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels

WMD Weapons of mass destruction

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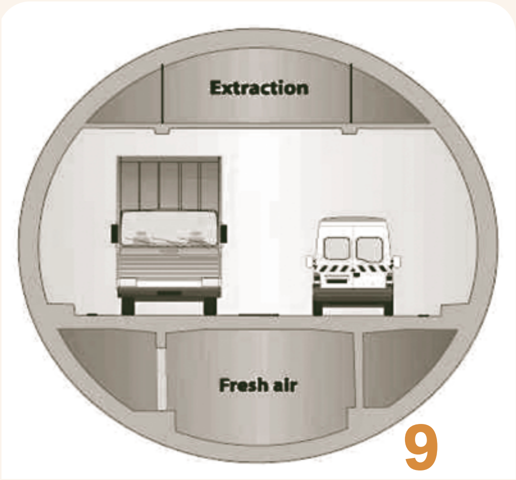
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INTRODUCTION

Increasing traffic congestion in urban areas and growing land values in the United States make underground structures increasingly attractive for highways and transit compared to other options. A tunnel can preserve the land above for parks, buildings, homes, and other uses while providing an efficient, cost-effective underground corridor to move people and goods. Unfortunately, only limited national guidelines, standards, or specifications are available for tunnel design, construction, safety inspection, traffic and incident management, maintenance, security, and protection against natural or manmade disasters.

An 11-member team was formed to study European practices on the aforementioned topics. This team consisted of three representatives from the Federal Highway Administration (FHWA), four representatives from State departments of transportation (DOTs), one representative from the Bay Area Rapid Transit District (BART), one representative from the Massachusetts Turnpike Authority who also represented the International Bridge, Tunnel, and Turnpike Association (IBTTA), one tunnel engineering design consultant, and the report facilitator. The scan was sponsored by FHWA, the American Association of State Highway and Transportation Officials (AASHTO), and the National Cooperative Highway Research Program (NCHRP). During late September and early October 2005, the team visited Denmark, France, Norway, Sweden, and Switzerland. In addition, the team had meetings with representatives from Austria, Germany, Italy, and the Netherlands. These countries were selected on the basis of desk scan findings that showed they are innovators in underground transportation systems.

The objectives of the scan were to learn what is being done internationally for underground transportation systems in the areas of safety, operations, and emergency response.

The focus of the scan was on equipment, systems, and procedures incorporated into modern underground and underwater tunnels by leading international engineers and designers. The study considered the following:

- Tunnel systems and designs that provide fire protection, blast protection, and areas of refuge or evacuation passages for users.
- Arrangements of the various components to maximize their effectiveness, assure inspectability and maintainability, and promote cost savings.
- Tunnel operations, including incident detection and deterrent technology, and incident response and recovery planning.
- Specialized technologies and standards used in monitoring or inspecting structural elements and operating equipment to ensure optimal performance and minimize downtime during maintenance or rehabilitation.

Regarding the safety and security aspects, the team was interested in learning about planning approaches, standards, manpower roles and responsibilities, communication techniques, and state-of-the-art products and equipment used to deter, detect, deny, defend, respond to, and recover from both natural and manmade disasters and other incidents.

Team members were interested in not only tunnel practices and innovations for highways, but also those for passenger and freight rail.

FINDINGS AND RECOMMENDATIONS

Team members identified a number of underground transportation system initiatives and practices that varied from those in the United States in some respect. The team recommended that nine of these initiatives or practices, briefly described below, be further considered for possible implementation in the United States. Little was discovered related to the threat from terrorism to underground structures, perhaps because of the confidential nature of this information or the lack of perceived need for such measures. The scan team learned that the Europeans consider response and safety measures already in place for crashes and other incidents to also be applicable for many terrorist actions.

The Europeans are doing extensive research resulting in innovative design and emergency management plans that consider how people react in tunnel emergencies. Because motorist behavior is unpredictable in tunnel incidents, Europeans make instructions for drivers, passengers, and tunnel operators as straightforward as possible to reduce required decisionmaking during an incident such as a tunnel fire. The nine initiatives and practices listed below relate to human factors, planning, design, and incident and asset management.

1. Develop Universal, Consistent, and More Effective Visual, Audible, and Tactile Signs for Escape Routes

The scan team noted that the signs Europeans use to indicate emergency escape routes are consistent and uniform from country to country. Emergency escape routes are indicated by a sign showing a white-colored running figure on a green background. Other signs that indicate the direction (and in tunnels, the distance in meters) to the nearest emergency exit also have the white figure on a green background, as used in European buildings and airports. All SOS stations in the tunnels were identified by the color orange. This widespread uniformity promotes understanding by all people, and helps assure that in the event of an emergency, any confusion related to the location of the emergency exit will be minimized. In addition, the team learned that combining the use of sound that emanates from the sign, such as a sound alternating with a simple verbal message (e.g., "Exit Here") with visual (and, where possible, tactile) cues makes the sign much more effective.

The U.S tunnel engineering community relies on National Fire Protection Association (NFPA) 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems, and NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways,* for fire protection and fire life safety design standards. These standards should be reviewed and revised as necessary to incorporate the most current technology and results of recent human response studies on identification and design of escape portals, escape routes, and cross passages.

2. Develop AASHTO Guidelines for Existing and New Tunnels

Single-source guidelines for planning, design, construction, maintenance, and inspection of roads and bridges have been in place for many years. NFPA has developed standards for safety in highway tunnels and passenger rail tunnels. The American Public Transportation Association (APTA) has general safety standards and guidelines for passenger rail operations and maintenance that incorporate some of the NFPA standards by reference. However, AASHTO does not have standards or guidelines specifically for highway or passenger and freight rail tunnels. Recently, the AASHTO Subcommittee on Bridges and Structures created a new committee, the Technical Committee on Tunnels (T–20), to help address this problem. T–20 should take the lead in developing AASHTO standards and guidelines for existing and new tunnels, working with NFPA, APTA, FHWA, and the appropriate TRB committees on standards and guidelines for highway and passenger and freight rail tunnels. T–20 should consider tunnel safety measures such as the Mont Blanc Tunnel emergency pullout area and variable message sign showing maximum speed limit and required vehicle spacing, as well as refuge room requirements.

3. Conduct Research and Develop Guidelines on Tunnel Emergency Management that Includes Human Factors

Tunnel design solutions may not anticipate human behavior, and consistently predicting the way people will behave in an incident is not easy. During emergency situations, human behavior is even harder to predict as the stress of the situation replaces intellect with curiosity, fear, or even panic. During a tunnel emergency, people often must be their own first rescuers and must react correctly within a few minutes to survive. Tunnel emergency management scenarios and procedures must take human behavior into account to be fully effective in saving lives. The European experience in human factor design provides a good basis for the United States to discover and include more effective measures for tunnel planning, design, and emergency response.

4. Develop Education for Motorist Response to Tunnel Incidents

During an emergency situation, most people do not immediately know what to do to save themselves and others. Motorists are their own first rescuers, and European studies indicate that self-rescue may be the best first response for a tunnel incident. For this to be an effective strategy, it is important to educate the public about the importance of reacting quickly and correctly to a tunnel incident, such as a fire.

5. Evaluate Effectiveness of Automatic Incident Detection Systems and Intelligent Video for Tunnels

The scan team learned of sophisticated software that—using a computer system interfacing with ordinary video surveillance cameras—automatically detects, tracks, and records incidents. As it does so, it signals the operator to observe the event in question and allows the operator the opportunity to take the appropriate action. This concept can also be applied to detect other activities and incidents in areas besides tunnels, including terrorist activities, crashes, vandalism and other crimes, fires, and vehicle breakdowns.

6. Develop Tunnel Facility Design Criteria to Promote Optimal Driver Performance and Response to Incidents

The Europeans found that innovative tunnel design that includes improved geometry or more pleasing visual appearance will enhance driver safety, performance, and traffic operation. For example, the full-size model of one section of the twin roadway tube for the A–86 motorway in Paris demonstrates the effectiveness of good lighting and painting to improve motorist safety. It is a particularly important consideration for a tunnel roadway section designed with limited headroom. Tunnel designers should evaluate the materials and design details that are incorporated to reduce risks to ensure that they do not pose other unacceptable hazards. For example, paint used to enhance the visual experience should not produce toxic fumes or accelerate fire.

7. Investigate One-Button Systems to Initiate Emergency Response and Automated Sensor Systems to Determine Response

The European scan revealed that one of the most important considerations in responding to an incident is to take action immediately. For this to be effective, the operator must initiate several actions simultaneously. An example of how this immediate action is accomplished is the "press one button" solution that initiates several critical actions without giving the operator the chance to omit an important step or perform an action out of order. On the Mont Blanc Tunnel operations center control panel, operators can initiate several actions by moving a yellow line over the area where a fire incident is indicated on a computer screen. This "one-button" action reduces the need for time-consuming emergency decisions about ventilation control and operational procedures.

The Europeans observed that tunnel operations personnel have difficulty keeping up with events like tunnel fires, and they believe that an automatic system using devices like opacity sensors can help determine the correct response. A closed-loop data collection and analysis system that takes atmospheric conditions, tunnel air speed, and smoke density into account may best control fans and vents.

8. Use Risk-Management Approach to Tunnel Safety Inspection and Maintenance

The scan team learned that some organizations use a risk-based schedule for safety inspection and maintenance. Through knowledge of the systems and the structure gained from intelligent monitoring and analysis of the collected data, the owner can use a risk-based approach to schedule the time and frequency of inspections and establish priorities. It makes more sense to inspect less critical or more durable portions of the system on a less frequent basis, and concentrate inspection efforts on the more critical or more fragile components. A risk-based assessment of the condition of facilities also can be used to make optimal decisions on the scope and timing of facility maintenance or rehabilitation. This method offers a statistical process to manage the tunnel assets.

9. Implement Light-Emitting Diode Lighting for Safe Vehicle Distance and Edge Delineation in Tunnels

The scan team noted that in several European tunnels, light-emitting diode (LED) lights were installed along the edge of the tunnel at regular intervals of approximately 10 to 20 meters (m) (33 to 66 feet (ft)) to clearly identify the edge of the roadway. These lights were either white or a highly visible yellow color. In some tunnels, spaced among these edge-delineation lights were blue lights at 150-m (490-ft) intervals. Motorists are instructed through formal (for truck and bus drivers) and informal driver education to keep a safe distance between them and the vehicle in front, and that distance is indicated by the spacing of the blue lights. This visual cue is more reliable than asking motorists to establish distance between vehicles using speed-based guidelines, such as maintaining one car length spacing for every 16 kilometers per hour (10 miles per hour) of speed. The LED markers are also less susceptible to loss of visibility because of road grime and smoke during a tunnel fire.

IMPLEMENTATION ACTIVITIES

The scan team has developed a detailed implementation plan for the nine recommended initiatives and practices. Included in the plan are a number of technical presentations and written papers at national meetings and conferences sponsored by FHWA, AASHTO, and other organizations to disseminate information from the scan. Also included in the plan is coordination with AASHTO, FHWA, NFPA, and APTA to advance these initiatives and practices, including assisting with the development of AASHTO standards and guidelines for highway tunnels and passenger and freight rail tunnels. Considerations for outreach to the public include the development of brochures and radio and television announcements. These and other planned activities are discussed in Chapter 3.

Introduction

BACKGROUND

Increasing traffic congestion in urban areas and growing land values in the United States make underground structures increasingly attractive for highways and transit compared to other options. A tunnel can preserve the land above for parks, buildings, homes, and other uses while providing an efficient, cost-effective underground corridor to move people and goods. The United States has about 500 highway, passenger rail, and freight rail tunnels, according to the Blue Ribbon Panel on Bridge and Tunnel Security sponsored by the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the Transportation Research Board (TRB). Unfortunately, only limited national guidelines, standards, or specifications are available for tunnel design, construction, safety inspection, traffic and incident management, maintenance, security, and protection against natural or manmade disasters.

OBJECTIVES

The objectives of the scan were to learn what is being done internationally for underground transportation systems in the areas of safety, operations, and emergency response. The focus of the scan was on equipment, systems, and procedures incorporated into modern underground and underwater tunnels by leading international tunnel experts. The study considered the following:

- Tunnel systems and designs that provide fire protection, blast protection, and areas of refuge or evacuation passages for users.
- Arrangements of the various components to maximize their effectiveness, assure inspectability and maintainability, and promote cost savings.
- Tunnel operations, including incident detection and deterrent technology, and incident response and recovery planning.
- Specialized technologies and standards used in monitoring or inspecting structural elements and operating equipment to ensure optimal performance and minimize downtime during maintenance or rehabilitation.

Regarding the safety and security aspects, the team was interested in learning about planning approaches, standards, manpower roles and responsibilities, communication techniques, and state-of-the-art products and equipment used to deter, detect, deny, defend, respond to, and recover from both natural and manmade disasters and other incidents.

Team members were interested in not only tunnel practices and innovations for highways, but also those for passenger and freight rail.

AMPLIFYING QUESTIONS

Amplifying questions were developed to help the foreign experts more fully understand the topics of interest to the scan team members. These questions, listed in Appendix A, were provided to the host countries before the scan.

HOST COUNTRIES

The scan team met with representatives from nine countries from September 23 to October 9, 2005. The team visited Denmark, France, Norway, Sweden, and Switzerland. While in Norway, the team also had meetings with a representative from the Netherlands. While in France the team had meetings with representatives from Germany and Italy, and while in Switzerland it met with a representative from Austria. These nine countries were selected on the basis of desk scan findings that showed they are innovators in underground transportation systems. The contacts in each country are listed in Appendix B, and the scan itinerary is in table 1 on the following page.

TEAM MEMBERS

The scan was sponsored by FHWA, AASHTO, and the National Cooperative Highway Research Program (NCHRP). The 11-member

Figure 1. *Scan team in front of Mont Blanc Tunnel firefighting truck. Standing (left to right) are two Mont Blanc hosts, team member Chris Hawkins, Mont Blanc host, and team members Mike Swanson, Mary Lou Ralls, M.G. Patel, Steve Ernst, Jesus Rohena, Harry Capers, Tom Margro, and Gary Jakovich. Kneeling are team members Don Dwyer and Wayne Lupton.*

team consisted of three representatives from FHWA, four representatives from State departments of transportation (DOTs), one representative from the Bay Area Rapid Transit District (BART), one representative from the Massachusetts Turnpike Authority who also represented the International Bridge, Tunnel, and Turnpike Association (IBTTA), one tunnel engineering design consultant, and the report facilitator. Team member contact information and biographical sketches are in Appendix C.

Table 1. *Scan itinerary.*

DAY, 2005 DATE	LOCATION	ACTIVITIES
Monday, September 26	Tronheim, Norway	Meeting with Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF) and with representative from Center for Tunnel Safety at Dutch Ministry of Transport, Public Works, and Water Management
Tuesday, September 27	Tronheim, Norway	Meeting with Norwegian Fire Research Laboratory (SINTEF NBL) and tour of E39 Motorway tunnels
Wednesday, September 28	Copenhagen, Denmark	Meeting with Copenhagen Metro
Thursday, September 29	Copenhagen, Denmark and Larnecken, Sweden	Meeting with Rambøll in Copenhagen, meeting with Oresundsbro Konsortiet and tour of Oresund Fixed Link tunnel, and tour of Oresund Operations Center in Larnecken
Friday, September 30	Malmo, Sweden	Meeting with Citytunnel, tour of Citytunnel Exhibition Center, and meeting with Swedish National Testing and Research Institute (SP)
Monday, October 3	Paris, France	Meeting with Cofiroute, tour of A86 Exhibition Center, tour of A86 East Tunnel, tour of A86/A13 tunnel interchange, and meeting with Citilog
Tuesday, October 4	Lyon, France	Meeting with Tunnel Study Centre (CETU) at French Ministry of Transport, Equipment, Tourism, and Sea, and with representative from German Research Association for Underground Transportation Facilities (STUVA)
Wednesday, October 5	Mont Blanc, France	Meeting with Italian representatives of Mont Blanc Tunnel Corporation and tour of Mont Blanc Tunnel
Thursday, October 6	Berne, Switzerland	Meeting with Swiss Federal Roads Authority and representative from University of Graz of Austria
Friday, October 7	Mitholz, Switzerland	Meeting with Berne-Loetschberg-Simplon (BLS) AlpTransit and Schneller Ritz & Partner, and tour of Loetschberg Base Tunnel

Findings on Underground Transportation Systems

In Europe, a tunnel is defined as an enclosed structure of 100 meters (m) (328 feet (ft)) or more in length. European countries have no definition of a "long" tunnel, but an approximate cutoff for routine tunnels is about 5 kilometers (km) (3 miles (mi)); longer tunnels are considered special tunnels. The United States National Fire Protection Association (NFPA) standard 502 defines a highway tunnel as "an enclosed roadway for motor vehicle traffic with vehicle access that is limited to portals," and provides minimum fire protection requirements for tunnels that are 90 m (300 ft) and longer.

Major tunnel incidents since 1995 have killed 713 people worldwide. From 1999 to 2001, several tunnel fires with multiple deaths occurred in Europe: 39 people died in the fire in the Mont Blanc Tunnel between France and Italy in March 1999, 12 people died in the fire in the Tauern Tunnel in Austria in May 1999, and 11 people died in the fire in the Gotthard Tunnel in Switzerland in October 2001 in which the temperature reached 1,000 degrees Celsius (°C) (1,832 degrees Fahrenheit (°F)) within a few minutes (see figure 2). These incidents caused significant concern about tunnel safety, resulting in half a dozen large European projects, including UPTUN (Cost-effective, Sustainable, and Innovative Upgrading Methods for Fire Safety in Existing Tunnels). One project, called SafeT (for "Safety in Tunnels"), is determining complementary aspects of the various projects and ensuring minimum duplication among the projects.

Fire in tunnels continues to be a major area of concern worldwide. Figure 3 (see next page) shows a portion of a pamphlet that gives general details on how to respond if a motorist encounters a fire in a tunnel. This pamphlet has become an official European Union (EU) document and is based on text by PIARC, the World Road Association (see *http://www.piarc.org).* PIARC is a nonprofit, nonpolitical association, previously known as the Permanent International Association of Roadways Congress. It has a number of technical committees and focuses on the exchange of knowledge on roads and road transport policy and practices within an integrated sustainable transport context.

Figure 2. *Gotthard Tunnel fire in October 2001. (SINTEF)*

Other safety concerns that continue to be investigated for solutions include dew and ice on windshields at portals that cause braking and rear-end crashes and lack of respect for stop lights at tunnel portals. The EU has a common incident reporting format for data collection.

Countries and Organizations Visited

Norway

According to the Norwegian Tunneling Society (*www.tunnel.no*), Norway has 881 road tunnels with a total length of 843 km (524 mi) and 700 railway tunnels with a total length of 316 km (196 mi). All are in rock. The majority of Norwegian road tunnels have one tunnel tube with two-way traffic.

The mountains and fjords of western Norway make tunneling a logical solution for routing motorways across this rugged terrain. The scan team learned that even with the recent tunnel fires in Europe, Norway continues to build tunnels because motorists welcome them because of their better driving conditions and increased safety compared to the alternatives of ferries, roads exposed to avalanches, roads closed during winter, longer driving distances, and driving in bad weather. However, a recent Gallup poll by an insurance company found that 500,000 Norwegians hesitate to use tunnels and 30,000 Norwegians never drive through tunnels. The reasons cited include darkness, narrowness, perception of limited vertical clearance, steepness, length, monotonous driving, fear of being underwater, and poor markings. Of those driving in the tunnels, 15 percent find it unpleasant and 60 percent do not know how to react to a tunnel fire incident.

From this poll it is apparent that the main challenges in Norway related to tunnels are to reduce the risk of critical events, construct tunnels to limit fear and worry, develop preparedness plans to minimize the consequences when incidents occur, and inform motorists in advance to increase the possibility of appropriate behavior. The

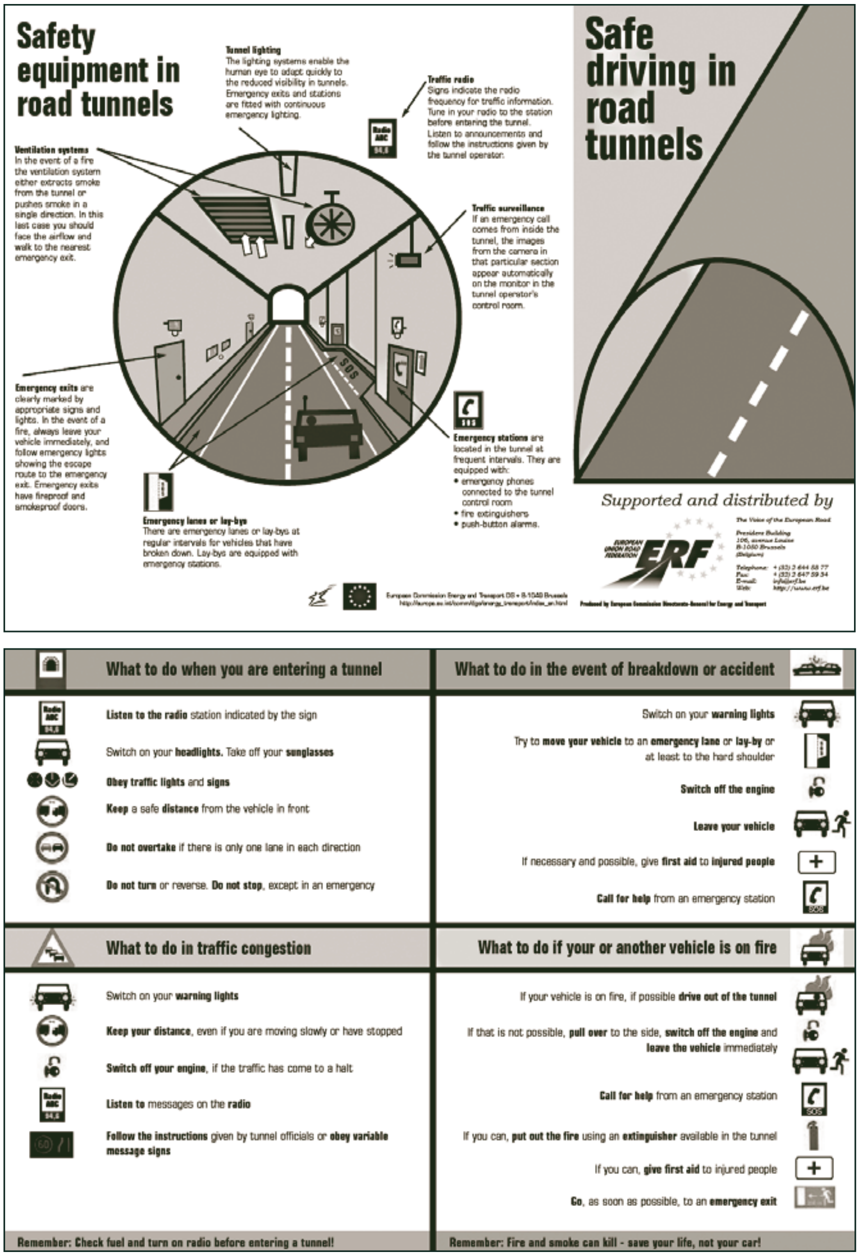


Figure 3. *EU pamphlet for motorists in tunnels.*

decisions and behavior of the motorists themselves are of vital importance in a tunnel fire incident. More specific information needs to be communicated to motorists because a better understanding among motorists will ensure more appropriate behavior.

The traffic crash rate in Norwegian tunnels is 0.13 incidents per million vehicle-kilometers, compared to 0.30 incidents per million vehicle-kilometers outside tunnels. The entrance-exit zones (portal areas) are the least safe areas of the tunnel. Norway has well-developed tunnel design specifications, and tunnels over 500 m (1,640 ft) long require a specific response plan for tunnel incidents.

For more information, see the Project Delivery section for discussion on the new E39 highway in Norway.

SINTEF

The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF), founded in 1940, is a nonprofit multidisciplinary research foundation with offices in Trondheim (headquarters) and Oslo. SINTEF has 1,810 employees and is the fourth-largest independent research institute in Europe. It has considerable experience and expertise in traffic management, traffic safety analysis, survey techniques, and human factors, and has a strong affiliation with the University of Oslo and the Norwegian University of Science and Technology. Public and private research contracts generate more than 90 percent of SINTEF's revenues. It has several departments working in the transportation area, including Transport Safety and Informatics, the scan team's host in Trondheim. SINTEF is an active member of the research teams for UPTUN in the human response area and L-surF (feasibility study for a **L**arge-**S**cale **U**nderground **R**esearch **F**acility on Safety and Security).

Activities include collecting various data for use in evaluating legislation, actual field performance data, and effects of design on motorist behavior. Safety in transport is related to the road user, who may be exposed as a pedestrian, bicyclist, or driver, all subjects of SINTEF's research to find a link between the road user and safety. Most SINTEF reports are public, and some are on the Internet. These reports are typically in Norwegian, although some have a short summary in English.

SINTEF has done extensive work in tunnel traffic management. Its research includes the adjacent network, since an incident in a tunnel has an impact outside the tunnel. Traffic management systems are used to monitor and control traffic in a tunnel and to manage the response to incidents. Researchers clarify and specify the different traffic constraints that should be used for planning and operating the system. They also enable different management schemes for different conditions, and enable a categorization of scenarios as the basis for automatic incident detection. The number of scenarios considered for use in traffic management systems needs to be a minimum to ensure manageability of gathering necessary data and developing responses. SINTEF researchers believe that automatic control of tunnel equipment should be used only for no-disturbance or periodic-disturbance scenarios; all other cases need human intervention using detailed response plans. Parallel and backup systems are required that will operate in various conditions, including smoke, high heat, and moisture. Response plans need to be made uncomplicated for the user in an emergency since drivers will act differently than expected. Because people panic in a fire, input from experts in human behavior is also needed.

SINTEF recommends that a variety of specialties be used in the process of designing a tunnel. Multidisciplinary teams are essential for good, safe designs. Fire brigades and the directorate of public roads both have input and different philosophies. Fire brigades want fail-safe systems resulting in zero risk, while the directorate, because of economic restraints, believes that the design must be based on an acceptable level of risk. The contingency plan for each tunnel is linked with the traffic management system.

SINTEF makes use of driving simulators to help determine driver reaction in various situations, including driving through tunnels. In addition, traffic simulation tools are useful in modeling traffic responses to various situations. Models of scenarios can be developed to show traffic reactions to different designs and to verify traffic scenarios.

For more information, see the Planning and Design section for discussion on the use of LED lights in the Grilstad Tunnel and the Incident Management section.

SINTEF NBL—Fire Laboratory

The Norwegian Fire Research Laboratory (SINTEF NBL) is an international leader in full-scale fire tests. In operation since 1934, it is the only fire research laboratory in Norway that does small to large and full-scale fire tests (see *http://nbl.sintef.no/*). Its focus is on fire safety testing. It has a large fire testing hall measuring 36 m (118 ft) long by 18 m (59 ft) wide by 28 m (92 ft) high for testing large objects. This testing hall can withstand the heat and smoke load of a 12-m^2 (129-ft^2) gasoline fire and 18-m (59-ft) high flames. The walls are specially designed for a continuous temperature load of 700 °C (1,292 °F).

The fire laboratory conducts tests on the fire resistance properties of various commercial products. These include materials such as surface coating and linings and building components such as wood and plastic pallets. Researchers perform fire suppression testing and have applied it on all types of objects, including buildings, boats, and planes. They have experimented with fires up to 40 megawatts (MW) in size with a temperature of up to 1,400 °C (2,552 °F). Most testing is done according to standards developed under the European Building Directive, which focuses on providing uniform performance standards, specifications, and test procedures for application across Europe.

Some Norwegian tunnels have been built with a polyurethane layer on the face of the concrete tunnel lining to minimize the accumulation of frost. Testing at SINTEF has shown that the insulation can be a fire hazard, so the insulation is being covered with shotcrete in some tunnels to mitigate this hazard.

For more information, see the Planning and Design section for discussion of SINTEF NBL work on fire suppression and experiments using an air curtain to control smoke.

The Netherlands

Dutch Ministry of Transport, Public Works, and Water Management

While in Norway, the scan team met with Evert Worm, head of the Center for Tunnel Safety. The center is part of the Tunneling Department in the Dutch Ministry of Transport, Public Works, and Water Management. Worm is also the chair of PIARC C3.3 Working Group 3 on Human Factors for Tunnel Safety.

The Netherlands Organization for Applied Scientific Research (TNO) is an independent research and development organization with 5,000 staff members and 14 institutes in various specialties that do contract research for industry and government, including the Dutch Ministry. TNO is a member of UPTUN and L-surF, and was a project leader for the September 2003 fire tests in the Runehamar Tunnel in Norway in collaboration with UPTUN partners SP and SINTEF NBL.

For more information, see the Planning and Design section for discussion of the Dutch Integrated Safety Philosophy expected to become law in 2006 and the integrated safety plan for the Westerschelde Tunnel. See also the discussion on Dutch escape route signs, LED lights, design fire size, and fire suppression systems.

Denmark

In 1990, Denmark embarked on an ambitious plan to improve Copenhagen's economy and make the region a center for European transportation. To accomplish this, it is taking the following steps:

- It constructed a fixed link between Copenhagen and Malmo, Sweden, to enhance the mobility and economic strength of the Oresund region.
- It is developing a new town area (Oresund) on undeveloped land on the south side of Copenhagen. The railway and motorway between the two countries will pass through this area.
- It is constructing a Metro in Copenhagen to serve the new town area.

These projects were financed by bonds, and it is expected that an increase in adjacent property values will pay for the infrastructure improvements. The payoff period was assumed to be 40 years. Construction loans for the Metro are repaid by income from the Oresund fixed link and the Metro, land sales, land taxes, and a small amount from partners.

Copenhagen Driverless Metro

The Copenhagen Metro concept originated in 1990. The transit project, a government-owned operation, aims to lower the traffic volume in urban areas, allowing more pedestrian uses. Aesthetics was a significant consideration for the project to help promote higher land values and tax base. The vision of the system was that it would be fast, reliable, safe, and clean.

A fully automatic system (driverless) vehicle was selected. Metro personnel assist users, collect fees, and provide a sense of safety. Separate tunnels are constructed for bidirectional traffic and escape doors are provided every 600 m (1,970 ft).

The project has two contracts for each of the three phases: one contract for the civil work and one for the stations. The stations were built first, and the tunnels were then constructed to connect the stations. The contract was design-build with operation for 5 years, plus maintenance for the civil work. The project started in October 2002 and is scheduled to be completed October 2007.

Tunnels were standard bored 4.9-m (16-ft) diameter bore tunnels with 70-centimeter (28-inch) walkways with handrails. Station placement was determined largely by surrounding development. Station construction was done top down to minimize community impact. The construction sequence was top slab, walls, excavation, and cast bottom slab. All but two stations are about 20 m (65 ft) below street level. Almost the entire length of the tunnels was bored through the limestone layer that underlies the city, minimizing the impact of this work on the community. Hands-on inspections are typical, with service vehicles and inspection platforms provided. In addition, standard details are available for typical repairs such as spalls and cracks. Standard inspection manuals are provided that also specify required inspector qualifications.

Consideration will be made in future work to provide more inspection access, as some details now require demolition to access. More attention will also be paid to water intrusion. Future contracts will also better define quality assurance responsibilities for inspectors. Watertightness of stations will be an item of larger focus.

Two train lines are now operational. The time interval between trains is 200 seconds, with a train in the station every 100 seconds during rush hour. Operations standards are governed by incentive-disincentive, with 98 percent reliability as the standard for satisfactory performance.

The Copenhagen Metro is open and proactive with the media. Its communications department is the biggest group in the company.

For more information, see the Planning and Design section and the Incident Management section.

Rambøll

Rambøll Denmark is part of the Rambøll Group, a consulting group with more than 4,000 employees at more than 70 offices covering the Nordic region and 50 additional locations outside the region. Rambøll Denmark provides technical consulting services in various fields, including infrastructure, transport, and traffic. Its services include operation and maintenance systems and risk management for tunnels.

For more information, see the Planning and Design section and the Maintenance and Safety Inspection section.

Oresundsbro Konsortiet

Oresundsbro Konsortiet is a company jointly owned by the Danish and Swedish governments. It owns and operates the Oresund Fixed Link, the 16-km (10-mi) coast-to-coast highway and passenger and freight rail link connecting Copenhagen, Denmark, and Malmo, Sweden. The link, which includes an 8-km (5-mi) long bridge and 4-km (2.5-mi) long tunnel, opened in 2000 and is jointly owned by the Danish and Swedish governments (see figure 4). Rail traffic is operated by the rail authority and is monitored by the train stations in Malmo and Copenhagen. Oresundsbro Konsortiet operates and maintains the nonrail portion. The link is critical to the Oresundsbro Konsortiet vision to see the Oresund Region emerge as a new European powerhouse in cultural as well as economic terms.

Figure 4. *Oresund fixed link between Copenhagen, Denmark, and Malmo, Sweden. Shown is the island portal and bridge approach looking toward Sweden.*

Oresund Fixed Link Tunnel—The tunnel portion of the Oresund link is located on the Copenhagen end. Because of concerns that a bridge close to Copenhagen's Kastrup Airport might present an obstacle to air traffic, the decision was made to construct a tunnel at the east end of the link. The immersed tunnel consists of two rail tubes, two two-lane road tubes, and a service/escape corridor. A 4-km (2.5-mi) long artificial island was built from dredging the channel and has an entrance to the tunnel. The tunnels typically carry 12,000 to 21,000 vehicles per day. A speed of 110 kilometers per hour (km/h) (68 miles per hour (mi/h)) in the open is normal, including in urban areas. The speed limit is restricted to 90 km/h (56 mi/h) in the tunnels. By law, no bicycles or pedestrians are allowed in the tunnels.

Oresundsbro Konsortiet does not have its own fire brigade or police; it depends on the local authorities for these services. Police patrol the entire link. Joint Swedish-Danish teams patrol two days a week, while on other days teams from one country or the other patrol.

The police have control authority over dangerous goods on the railway. Explosives are allowed through the tunnel if under 1 ton. The Economic Council of Europe is developing new categories for hazardous loads through tunnels that are scheduled to become effective July 1, 2007. If site personnel see dangerous goods markings, they will attempt to make the vehicle turn around, and will report it to the police if they fail.

Many safety considerations were included in the formal risk analysis for the tunnel design. Eight years before commissioning the link, an advisory group was formed to provide advice on safety issues and how to build and operate the link. The advisory group included the fire brigade. Oresundsbro Konsortiet has its own safety pamphlet.

In response to the Madrid and London incidents, Oresundsbro Konsortiet plans to examine its entire procedures for security (e.g., the card access system, locations where terrorists could place explosives, and how to apply elevated alert levels). Danish authorities are assisting with this effort.

For more information, see the Incident Management section and the Maintenance and Safety Inspection section.

Sweden

Citytunnel Railway

The Citytunnel (Citytunnelln) Railway is a Swedish National Rail Administration project that includes 17 km (10.5 mi) of electrified two-track railway and provides the Swedish link to the Oresund Fixed Link. The Citytunnel will connect the Malmo area of Sweden with the train that crosses the Oresund Link from Copenhagen. (The entire Oresund region has about 3.5 million people. Two-thirds are on the Danish side and one-third in Sweden.) This passenger rail project includes both commuter rail and intercity rail service and is anticipated to impact the entire Oresund region. The trains are electric only, no diesel. The tunnel geometry is designed for 200 km/h (120 mi/h). The slowest section has a design speed of 80 km/h (50 mi/h), increasing to 160 km/h (100 mi/h).

The total project cost is SEK9.45 billion (US$1.19 billion) in 2001 value. Originally the city of Malmo, the third-largest city in Sweden with a population of 270,000, funded SEK1 billion (US$125 million). The Skane region and the Swedish Railway Authority were the other two original funding sources, while EU made a small contribution. These funding sources were later rolled into the Swedish National Rail Administration. Construction of Citytunnel will take 6 years. Construction started in March 2005 and is scheduled to end in 2011. In addition to the railway, three new stations will be constructed: a below-ground extension of the existing Malmo Central Station, the below-ground Triangeln Station, and the above-ground Hyllie Station. When completed, Malmo Central Station tubes will carry 34,000 travelers per day, Triangeln Station will serve about 37,000 riders per day, and Hyllie Station will serve about 16,000 riders per day.

Citytunnel encountered community resistance to the project because of concerns about potential damage to existing infrastructure caused by the new facilities. Because of these concerns, Citytunnel added an extensive exhibition center for community outreach to educate the public on the reason for and the scope of the project. The project will increase competitiveness of the area, renew vitality, ease traffic congestion, reduce pollution by reducing cars on the road, and provide a safe, efficient, environmentally friendly, and sustainable transportation system.

For more information, see the Planning and Design section and the Incident Management section.

Swedish National Testing and Research Institute

The Swedish National Testing and Research Institute (SP) is a wholly government-owned institute that does commercial testing and has a 10 percent taxpayer subsidy. It has 830 employees in Sweden who work in a variety of technical disciplines. The Fire Laboratory has a staff of 50 and conducts research and testing both nationally and internationally (in approximately equal portions). Its tunnel fire research began in 1993 as part of the Eureka tests started in Norway involving a number of organizations. SP projects include UPTUN, FIT (Fire in Tunnels), and L-surF. The scan team's host was a research scientist with SP Fire Technology.

The industry focus for tunnel fire safety is on both technical aspects and emergency response. SP officials believe that more emphasis is needed on driver behavior and vehicle performance to focus on prevention instead of reaction.

SP officials emphasized these findings from their tunnel fire research:

- Vehicles burn, not tunnels.
- People do not behave as engineers would like them to behave.
- Fires can "jump" from one vehicle to another and involve more vehicles (and therefore more fuel) than expected.
- Although the severity of fires is normally discussed in terms of fire size (heat release rate measured in megawatts), the rate of fire growth is equally or even more important and must be evaluated.
- The height of the tunnel ceiling affects the rate of fire growth. Low ceilings increase heat.
- Semi-trailer cabins must be built of noncombustible material (as is more common in the United States).
- Ventilation promotes the spread of fire, and longitudinal ventilation can promote the spread of fire longitudinally in the tunnel.
- Fire departments need clear response plans supplemented by training and drills.
- Intentional acts of destruction are considered a new threat.

Frequently asked questions are the following:

- What design fire should be used—5, 15, 30, 100, or 200 MW?
- Are standard temperature curves a better way to define tunnel fires?
- When should ventilation be started, how much should be used, and in what direction should it be applied?
- What is the required distance between escape routes?
- How large a fire can the fire department handle?
- Where should spray or water mist systems be introduced? What type of system should be used?

SP recommends the following action:

- Improve the fire resistance of heavy trucks.
- Take into account the unpredictable behavior of people in a fire situation.
- Design escape routes that people can easily understand and educate them on their use.
- Use transverse exhaust vent systems instead of longitudinal ventilation for improved smoke control.
- Consider installing simple and robust suppression systems in high-traffic tunnels.
- Make sure tunnel design features provide the fire brigade with a reasonable chance of success in a fire situation.

A report comparing fire evaluation methods will be available soon at the FIT Web site at *www.etnfit.net.*

Runehamar Tunnel Fire Test—In September 2003, four large-scale fire tests using wood and plastic pallets were conducted in the abandoned Runehamar Tunnel owned by the Norwegian Public Roads Administration on part of a road system destroyed in a landslide. SP led the testing in collaboration with UPTUN partners TNO and SINTEF NBL. Different semi-trailer fire loads were used, and the highest peak heat release rate ever measured in a tunnel fire test was registered at higher than 200 MW. Gas temperatures in the vicinity of the fire registered above 1,350 °C (2,460 °F). The objective was to observe the rate of fire growth and evaluate how the use of fire suppression or ventilation fans would affect the ability of users inside the tunnel to escape.

Observations included the following:

- The level of smoke rises very rapidly. In 5 minutes the area is completely engulfed in smoke. People have very little time, only 1 or 2 minutes, to get away.
- Smoke will flow in the direction of natural ventilation.
- The probability of misunderstanding the direction of airflow in the tunnel is high.
- If fire suppression is used to keep the fire below 30 MW, it is likely that people will be able to escape.

The following conclusions are drawn from these observations:

- If the expectation is that the users will evacuate immediately, the fans should be turned on to full power.
- If the expectation is that users will stay in their vehicles, it is best to use fire suppression. Human behavior studies have shown that, contrary to responses on surveys, people tend to stay in their vehicles much longer than they should.

For more information, see the Planning and Design section for discussion on SP work on design fire size, fire suppression systems, and ventilation systems.

France

A86 West Beltway Tunnels

The A86 West project is the missing link that will complete the second beltway around the city of Paris (see figure 5). The existing beltway is called the "Peripherique." The goals of the A86 West project are to complete the second beltway, improve the commute between suburbs, and reduce congestion. The project is expected to reduce surface traffic by 15 percent. No public funds are being used for the project.

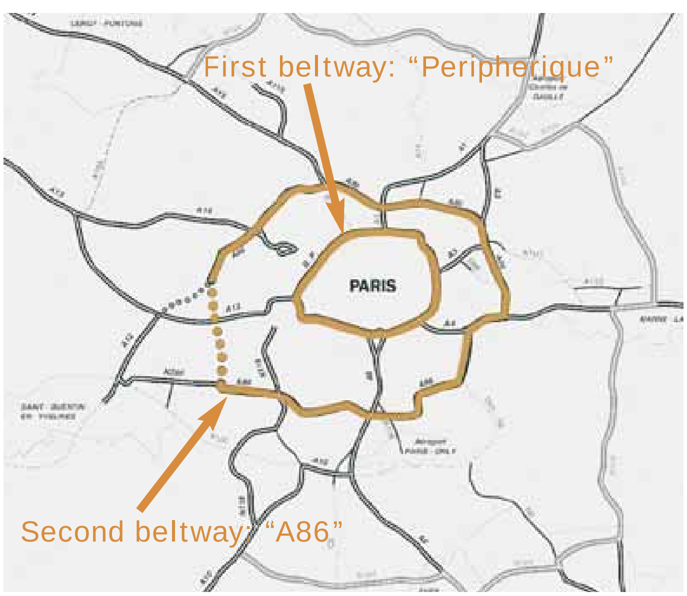


Figure 5. *A86 West Beltway project. (Cofiroute)*

The project was originally proposed in 1988. Major construction began in 1997, but the project was challenged and construction was stopped in 1998. The project encountered opposition from public officials who were concerned about the safety of the tunnel after the Mont Blanc Tunnel fire. It was decided that the project would use new French tunnel safety regulations developed after the Mont Blanc fire (e.g., the tunnels will include twice the number of refuge rooms). Construction began again in 2000 after officials were satisfied that the tunnels would be safe. The project includes an East Tunnel available to cars only and a West Tunnel (see figure 6) available to both cars and trucks. The scan team meetings focused on the East Tunnel only.

Cofiroute—Cofiroute is the operator and SOCATOP is the design-build contractor for the A86 West project, a €1.7 billion (US$2 billion) project. Cofiroute, created in 1970, was the first private highway operator in France and now operates 885 km (550 mi) of French highways. It has a contract with the French Highway agency to operate the A86 West project for 70 years. Tolls will vary during the day according to congestion, with high tolls during rush hour.

East Tunnel—The first phase of the East Tunnel is scheduled to open in 2007 and the second phase in 2009. The tunnel has two levels, one for each direction of travel, and is for passenger cars only. Each level will have two traffic lanes and a breakdown lane. The ceiling height in each level is 2.54 m (8.33 ft) and the clearance is 2 m (6.5 ft). The tunnel is being built using an 11.5-m (37.7-ft) diameter tunnel boring machine (TBM). To protect the environment, a very compact underground interchange with up to three levels of ramps was designed. The project will include tree planting at the ground surface in this area.

The tunnel will have pressurized refuge rooms for up to 50 people every 200 m (656 ft). See figure 7 (on page 10). Each level of the tunnel will have independent ventilation. The ventilation system is longitudinal during normal operation with extraction capability for smoke management during a fire in the tunnel. Well-marked exits and refuge rooms with bright colors and lights are used to attract the driver's attention in the tunnel. The tunnel will have one emergency access every 800 m (2,620 ft) for firefighters. A water mist sprinkler system is being considered for the tunnel.

The tunnel will be monitored 24-7 by a staff of 15. More than 400 cameras will be located inside the tunnel and at the access ramps. Cameras will be fitted with automatic incident detection and permanent digital recording. The tunnel will be illuminated with 10.5 candelas per square meter to improve safety. Current French regulations require 6 candelas per square meter. The operator will control the traffic inside the tunnel by detecting incidents, informing drivers what to do during incidents, and activating the emergency response plan. Emergency vehicles with a 2-m (6.5-ft) height have been ordered for fighting fires and assisting motorists inside the tunnels. Three ambulances with a 2-m (6.5-m) height will be parked at the three operation centers. See figure 8 (on page 10).

An exhibition center was created to explain the tunnel project to local citizens and public officials, who were initially opposed to the project. The full-size model of one section of the twin roadway tube allows users to experience the tunnel and demonstrates the effectiveness of good lighting and painting (see figure 9 on page 11).

Citilog—Citilog is a private company based in Paris that was formed by researchers in 1997 to provide technology solutions for use in tunnels and other transportation operating environments. Its services are being used on the A86 West project.

The A86 West project will use cameras with an automatic detection system that allows the tunnel operator to be proactive. The technology precisely interprets video images, discerns anomalies, and alerts transportation professionals to events occurring in the tunnel. It provides both the most current image of the area of an incident and images of activities that occurred just before the event. The system captures the information the operator needs to make the correct response decision. The images can be used for timely response to emergencies and can provide enhanced security at critical locations. This system can be used to detect a person walking in the tunnel after the train has entered or departed the tunnel. It also can be used to detect a package or object that has fallen from a moving vehicle and smoke inside the tunnel. When the camera detects an object or smoke, the system sounds an alarm to attract the operator's attention.

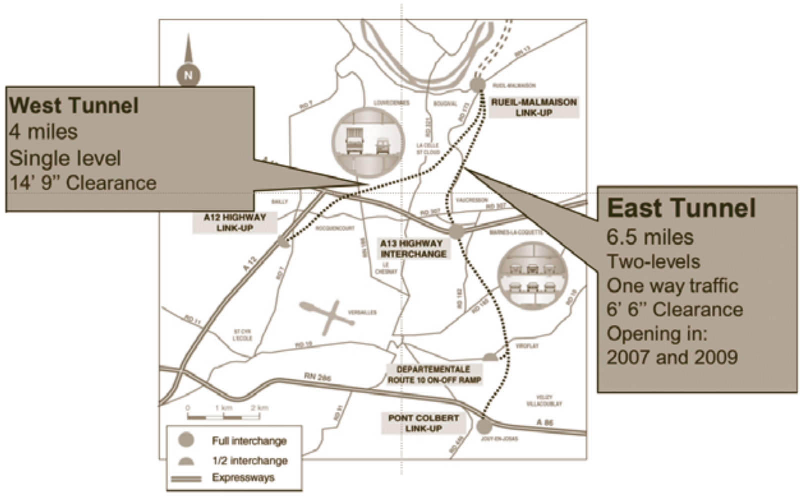
Concern has been expressed about the impact of cameras on the privacy of drivers. If used to read licenses plates in a crash, the cameras will zoom in to recognize the plates but not the drivers' faces.

The company can perform some system maintenance from a remote location. The system cost is about €4,230 (US$5,000) per camera for software installation.

CETU

In Lyon the scan team met with representatives from the Tunnel Study Centre (CETU) of the French Ministry of Transport, Equipment, Tourism, and Sea. CETU, which is part of the Road General Directorate, has seven departments with 90 staff members. The expertise of the multidisciplinary staff ranges from research engineering to equipment and operations. CETU's basic mission is to develop methodology and regulations for road tunnels based on the complementary functions of research, engineering, and coordination with various professional associations. CETU's efforts include issuing technical reports and recommendations, drafting regulations and standards, applying regulations, checking projects for conformance with regulations, and serving as the Secretariat of the National Commission for Safety in Road Tunnels.

CETU officials offered that they did not have good information on human factors behavior to incorporate in tunnel design or operations emergency response procedures. They said they were undertaking studies in human behavior to integrate into the planning and design process for tunnel safety as well as to develop driver education tools. This includes using sound, visual means, and real-time information transmission via changeable message signs. In the area of driver education, CETU has been



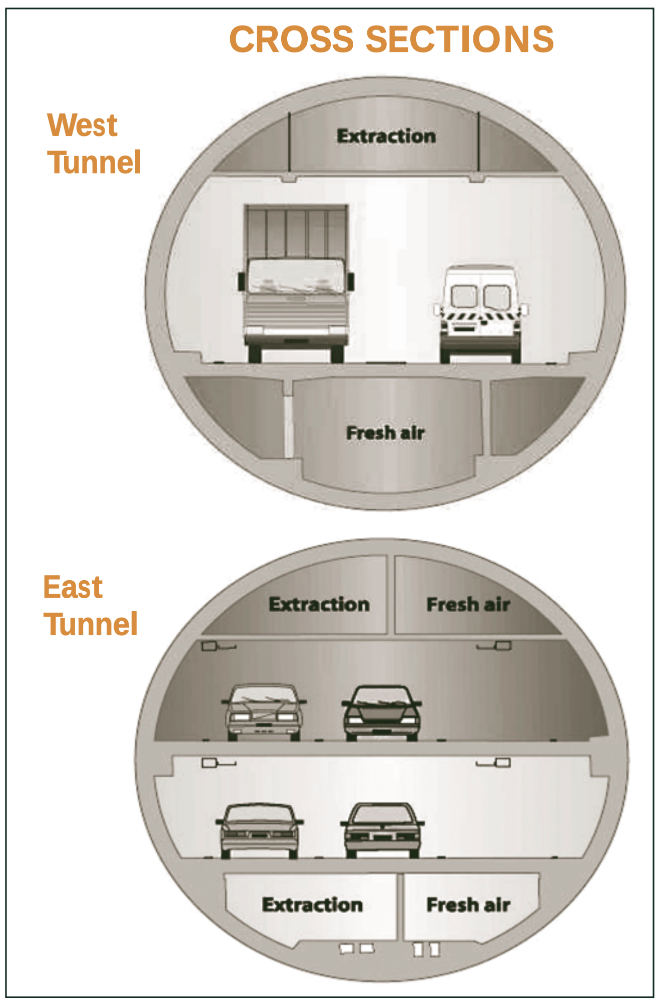


Figure 6. *Tunnels on the A86 West Beltway project. Top: West and East tunnels. Bottom: cross section of tunnels. (Cofiroute)*

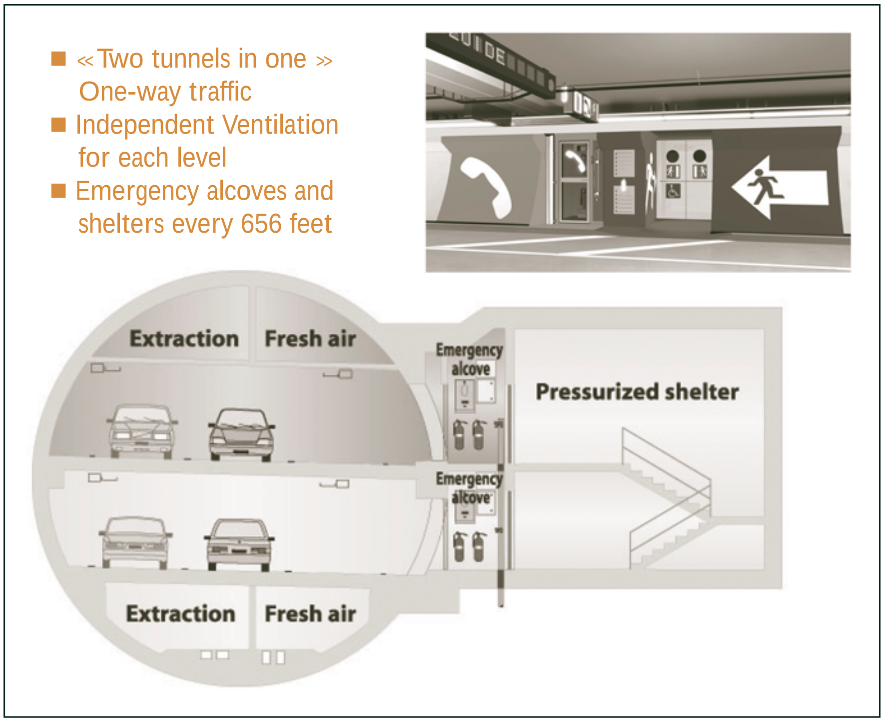


Figure 7. *A86 West Beltway East Tunnel emergency facilities. Top: cross section of emergency facilities. Bottom: example of emergency alcove. (Cofiroute)*

asked to evaluate a film prepared for drivers of heavy vehicles.

CETU officials provided an explanation of their approach to tunnel data acquisition, monitoring, control, and communication. The tunnel operator receives information through two linked but separate fiber-optic communication trunk networks. Each trunk network is a dual redundant loop system. One network provides security-related information such as telephone, radio, and video surveillance. The other network is used primarily for maintenance purposes and provides information on electrical, mechanical, and information system status.

For more information, see the sections on Planning and Design, Incident Management, and Maintenance and Safety.

Mont Blanc Tunnel

Located on the French-Italian border, Mont Blanc is the highest peak in the Alps at 4,807 m (15,771 ft). Opened in 1965, the Mont Blanc Tunnel brings together two Alpine regions, the Arve Valley in France and the Aosta Valley in Italy. The tunnel is 11.6 km (7.2 mi) long and 8.6 m (28 ft) wide and has over 2 km (6,500 ft) of mountain above it. It averages more than 4,000 vehicle crossings per day.

In March 1999, a fire in the Mont Blanc Tunnel left 39 dead. Immediately after this disaster, a French-Italian steering committee was formed to develop new rules and designs. From 2000 to 2002, the tunnel was redesigned and rebuilt and tunnel management was restructured. Before the fire, the Italian and French companies each managed its own half of the tunnel. Now one company, the European Economic Interest Group (EEIG-TMB), manages the entire tunnel, combining both French and Italian interests with one control room and one incident commander.

EEIG-TMB has 180 employees, half French and half Italian. It has three members on its board of directors: one from France, one from Italy, and a general manager who changes every 30 months. The general manager was initially from France and is now from Italy.

EEIG-TMB has four departments with 40 to 50 employees in each: administration, toll and customer relations, safety (in charge of safety and traffic management inside and outside the tunnel), and maintenance (in charge of routine maintenance and new projects and investments). EEIG-TMB emergency response procedures were used to develop the French regulations.

The EEIG-TMB safety department is in charge of the control room, safety team, and traffic management with real-time information system. Shifts work 24 hours a day, 7 days a week, and each shift has 14 employees, including 10 firefighters. The tunnel has three fire stations: one at each portal and one in the middle. Maintenance systems are tested every day, and a fire test is conducted weekly.

Full-scale safety exercises are conducted every 3 months in conjunction with CETU. For this exercise, the tunnel closes Monday at 7:30 p.m. and opens Tuesday at 6 a.m. The public is notified of the

Figure 8. *Special emergency vehicles for the A86 East Tunnel: (left) firefighting vehicle and (right) ambulance. (Cofiroute)*

closing dates in the newspaper and on the Internet. The exercise consists of two parts, one for training and one for routine maintenance. The training, which is videotaped, is done to improve organization and cooperation among the rescue services, including firefighters, paramedics, and police from both countries. This training improves cooperation since the two countries have different procedures and may uncover problems with the systems and the response organization. A typical exercise includes 100 emergency response personnel, 40 vehicles, and 30 people with simulated injuries. Participants do not know the specifics of the simulated incident beforehand. A yearly fire exercise is conducted in collaboration with CETU.

For more information, see the Planning and Design section for discussion on escape routes, LED lights, and ventilation systems. See also the Incident Management section.

Germany

STUVA

Joining the meetings with CETU in Lyon was Dr. Alfred Haack of the German Research Association for Underground Transportation Facilities (STUVA), the research arm of the German government. STUVA is a nonprofit, private organization with 225 corporate members, including contractors, suppliers, consultants, academia, and railway and metro operators. STUVA has two departments, one for operations and one for structural issues. Operations department activities include managing ventilation, accommodating disabled passengers, and managing transit operations. Structural department activities include those related to design, construction, and quality assurance. STUVA has also become involved with many international working groups and professional associations, including the International Tunneling Association, German Tunneling Association, and UPTUN. It is involved in several projects, including SafeTunnel, L-surF, and the European Safety Tunnel.

Haack offered that the question of how humans react in emergency situations is a significant issue and that we do not have definitive information to use in tunnel design and operations for emergency incidents. All agreed that human factors behavior is important for tunnel design and operation and that much more information is needed in this area.

Haack suggested that further work should be done to improve the fire resistance of heavy vehicles (trucks). He noted the lack of progress in this area for trucks compared to the European Norms (Standards) and German standards for the construction of rail rolling stock. Material composition and fire rating are included in these rail standards.

For more information, see the Planning and Design section and the Incident Management section.

Switzerland

In Berne, the scan team was hosted by representatives of the Swiss Federal Roads Authority (FEDRO), the Swiss equivalent of FHWA. FEDRO is responsible for administration of the highway program in the country. FEDRO developed the Switzerland tunnel ventilation directive published in 2004.

Figure 9. *Model of A86 twin roadway tube. Top: full-size model of one section. Bottom: scale model of twin tube.*

In Mitholz, the scan team was hosted by representatives of BLS AlpTransit AG, the main contractor for the Loetschberg Base Tunnel construction, and by representatives of Schneller Ritz & Partner, the design firm for the project. Schneller Ritz & Partner was instrumental in developing the 2004 Swiss Standards Association (SIA) design codes for road and railway tunnels.

For more information, see the Planning and Design section for discussion on the Swiss design codes.

Gotthard Road Tunnel

The Gotthard Road Tunnel is part of the A2 Motorway in the Swiss Alps, which serves heavy goods traffic between Germany and Italy. It eliminates 30 km (18 mi) of a twisting mountain pass that is closed up to 6 months of the year because of weather conditions. The tunnel, 16.9 km (10.5 mi) long, is one of the longest road tunnels in the world. Construction began in 1969 and the tunnel was opened in 1980. It quickly attracted 6.8 million vehicles per year. For more information, visit *www.gotthard-strassentunnel.ch.* Information is also in English.

Several fires in the Gotthard Tunnel have resulted in people staying in cars and dying in as little as 10 minutes, tunnel roof collapse, flashover from vehicle to vehicle, and confusion in getting to refuge rooms. These incidents show the importance of self-rescue.

For more information, see the Planning and Design section and the Incident Management section.

Loetschberg Tunnel

In 1998 the Swiss voted to modernize their rail system and shift transalpine transit traffic from road to railway. Funding was allocated to build the Loetschberg base tunnel, a rail tunnel intended for all types of trains, including high-speed passenger trains with speeds up to 250 km/h (155 mi/h) and transport of all types of goods and materials. The tunnel will extend from Frutigen in the Kander Valley to Raron in the Rhone Valley in the southwestern part of Switzerland. The tunnel length will be 34.6 km (21.5 mi), with a total length of all rail, service, and connecting tunnels of 88 km (54.7 mi). The tunnel will have a capacity for 110 passenger and freight trains per day.

When complete, the tunnel will have dual tubes for its entire length to maintain efficient two-way traffic flow. However, when it first opens in 2007 after the completion of Phase 1, the tunnel will have only one tube for a portion of its length. Traffic will have to be reversed in this portion as necessary to enable the single tube to accommodate bidirectional traffic.

Passenger trains using the tunnel are specially made and have pressure control in the cars to maintain passenger comfort. The trains will run on electricity power by two separate systems. One will operate at 16.7 Hertz (Hz) and feed power to the train itself. The other system will operate at 50 Hz to feed power to all tunnel systems except the train. Each power system will have two supply sources so that power can be supplied from either the north end of the tunnel or the south end. This redundancy will enable shutdown for maintenance or switching in case of malfunction of one supply. The control center for the tunnel is located 10 km (6.2 mi) away from the north end of Thun.

The tunnel drainage system incorporates sedimentation or cooling ponds to ensure that water draining from the tunnel system does not have adverse environmental effects on the Rhone River.

Requirements for construction safety and security are given high importance. The Swiss National Insurance Company insures workers against injury. General requirements provide guidance to the contractor for developing a comprehensive safety program to safeguard workers. The employer has the primary responsibility to take all necessary measures and establish worksite rules to protect employees, and employees are obliged to follow the employer's rules. Construction safety features include the following:

- Electronic information tags on hardhats to ensure that all employees who have entered the tunnel are accounted for.
- A control room to provide complete oversight of the tunnel construction alarm systems.
- Underground medical posts.
- Emergency breathing apparatus that employees can keep near their work locations.
- Safety containers in the work area that can hold up to 12 people and provide air for up to 4 hours.

For more information, see the Planning and Design section and the Incident Management section.

Austria

Austria has almost 100 road tunnels longer than 1,000 m (3,280 ft) and half a dozen of the world's longest railway tunnels ranging to over 12.5 km (7.7 mi). When the average number of daily vehicles per lane crossing an Austrian tunnel is greater than 10,000, a separate tube is constructed, as defined in the European Directive on Minimum Requirements for Safety in Road Tunnels (2004/54/EG).

Joining the scan team meetings in Berne, Switzerland, to discuss ventilation issues was a professor-researcher from the University of Graz in Austria. The scan team learned of a recent incident in an Austrian road tunnel in which a fire on a tanker truck in the tunnel demonstrated the unpredictability of human behavior as well as the rapid growth of a vehicle fire. In this instance, even trained police officers did not show familiarity with the tunnel fire safety equipment. Shortly after the incident was identified, the operations center stopped traffic entering the tunnel and opened cross tunnels to evacuate those already inside. The driver tried ineffectively to extinguish the fire using extinguishers from his vehicle and from the pullout area. Police responded but did not attempt to extinguish the fire. Tunnel maintenance staff eventually extinguished the fire with the available tunnel fire hoses. The fire brigade response time was 26 minutes.

For more information, see the Planning and Design section for discussion on design fire size, fire suppression systems, and ventilation systems.

Plabutsch Tunnel

The Plabutsch Tunnel is Austria's second-longest road tunnel. It is located in the southeastern region of Austria, in the province of Styria next to the region's capital, Graz. The tunnel is one of several major tunnels along the A9-Pyhrnautobahn motorway, which links central and southeastern Europe. The 10-km (6.2-mi) long tunnel opened in 1987 as a single-bore tunnel with bidirectional traffic. In 2004 a second bore was opened and the first bore was refurbished. Safety features used in the tunnel include fireproofing for all energy supply cables inside the traffic room and traffic monitoring by closed-circuit television (CCTV) with tunnel information displayed in fully graphical mode.

For more information, see the Planning and Design section.

KEY OBSERVATIONS

Major European Tunnel Research Programs

The scan team met with representatives working on two major European tunnel research projects, UPTUN and L-surF. These projects are described below.

UPTUN (http://www.uptun.net/)

UPTUN (2001–2006) is the acronym for Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing Tunnels, a large European project funded by the European Commission to find cost-effective means to upgrade tunnel safety. The project involves 42 EU partners and has a budget of US$19.3 million. UPTUN partners include scan team hosts SINTEF, SP, CETU, and STUVA.

The two main outputs of UPTUN are 1) development of innovative, cost-effective technologies and assessment of existing technologies for tunnel applications, with a focus on technologies in the areas of detection and monitoring, mitigation measures, influencing human response, and protection against structural damage; and 2) development, demonstration, and promotion of a risk-based evaluating and upgrading model for safety level evaluation, decision support models, and knowledge transfer. The spinoff desired from this work is the restoration of faith in tunnels as safe parts of the transportation system, the leveling of trade barriers imposed by supposedly unsafe tunnels, and an increased awareness by stakeholders of the necessity to develop initiatives to link all relevant research.

UPTUN has seven work packages (WP):

- WP 1—Prevention, detection, and monitoring
- WP 2—Fire development and mitigation measures
- WP 3—Human response
- WP 4—Fire effects and tunnel performance: system structural response
- WP 5—Evaluation of safety levels and upgrading of existing tunnels
- WP 6—Fire effects and tunnel performance: system response
- WP 7—Promotion, dissemination, education/training, and socioeconomic impact

WP 1 (prevention, detection, and monitoring) has five products. The database of European tunnels produced in WP 1 is ready. Since it is difficult to describe incidents uniformly, one must be careful using the data. It has technical systems and recent incidents. Reports are scheduled to be published in September 2006. The second and third products—incident analysis and recommendations for prevention solutions, and detection and monitoring systems—are completed. The last two products—new technology and improvements in existing techniques and tests on new technologies and reports—are scheduled to be ready in a few months.

WP 2 (fire development and mitigation measures) also has five products. The design fire scenarios and the acceptance criteria for engineering are ready and are scheduled to be available next year. The efficiency of current fire mitigation equipment, the models describing major influences of mitigating measures on design scenarios, and the guide for engineering cost-effective mitigation systems are scheduled to be ready in 2006.

WP 3 (human response) has four products. Current knowledge and measures, the role of human response in tunnel incidents, and methodologies and systems for handling critical situations are ready. Crisis management of rescue teams is the only work not yet completed. Some EU projects have U.S. participation, but this one does not. The United States, Japan, China, South America, and Australia have exchange through PIARC.

WP 4 (fire effects and tunnel performance: system structural response) has six products. The critical evaluation of burnt tunnel structural data, damage investigation methods, and structural fire test data are ready. The evaluation of spalling risk, repair and recovery procedures, and safety level definition are ongoing work.

WP 5 (evaluation of safety levels and upgrading of existing tunnels) will combine the outputs of other work packages to get a procedure for formulating a new level and describe how to achieve it. Other countries are also bringing in their views; it will be a mix. The five products are a comprehensive inventory of tunnel safety features, criteria to evaluate tunnel safety levels, a procedure for the holistic evaluation and upgrading of safety levels, upgrading recommendations, and the financial and socioeconomic impact of upgrading the tunnels. This work is ongoing.

WP 6 (fire effects and tunnel performance: system response) has four products: full-scale tests, test data on tunnel performance, a validation report on the theoretical model of WP5, and recommendations on upgrading of existing tunnels. The full-scale tests took place in February 2005 in Italy.

WP7 (promotion, dissemination, education/training, and socioeconomic impact) has six products: a report on economic impact; cooperation with running and future (extra) European projects; a European Tunnel Safety Board; criteria for informing (non) governmental bodies, institutions, and tunnel owners; layout for training and education programs; and promotion material. Some reports are ready; two will follow. One interesting development is that discussions are ongoing to develop European safety laws.

All deliverables are scheduled to be available in September 2006.

L-surF (http://www.l-surf.org)

The L-surF group (feasibility study for a **L**arge-**S**cale **U**nderground **R**esearch **F**acility on Safety and Security) is a new 3-year (2005–2007) initiative that will be Europe's future core of tunnel research and development. The objective is to build a strong new European organization dealing with tunnel testing, research, training, and development of different products. It is a major EU-supported activity focused on safety and security in underground infrastructures within the Sixth Framework Programme of research funding. It has a budget of 3.3 million (US$3.9 million), with the goal of harmonizing safety and security in Europe, bringing research and development to the forefront with large full-scale tests, and providing a means to promote tunnel research on safety and security internationally. After 3 years, the plan is to have a set of drawings that show how a center with all tunnel research in Europe will look.

The L-surF design study includes work packages with different partners responsible for different tasks, such as the following:

- Describe the facility construction plan based on a new concept for easily creating contours, shapes, and sizes of needed enclosed spaces and other aspects such as installations and environmental impacts.
- Describe the latest available sensor technologies.
- Evaluate the research needs and outline the research and development activities.
- Develop an integration process for the existing and projected national facilities with competence and researchers, thus restructuring and improving the relevant EU competence while simultaneously showing ways to more efficiently use research and development funds.
- Describe the budget and fundraising plans for the different stages in setting up the facility.
- Include a business plan for a new legal entity dedicated to establishing L-surF.

Core member organizations for this initiative are the following:

- VSH, Versuchsstollen Hagerbach AG, Hagerbach Test Gallery Ltd., Sargans, Switzerland, the leading partner.
- SP Fire, Swedish National Testing and Research Institute, Boras, Sweden.

- STUVA, German Research Association for Underground Transportation Facilities, Cologne, Germany.
- TNO, Netherlands Organization for Applied Scientific Research, Delft, Netherlands.
- NBL, SINTEF NBL, Trondheim, Norway.
- INERIS, Institut National de l'environnement industriel et des risques, Verneuil en Halatte, France.

Planning and Design

Standards, Safety Approaches, and Design Issues

2004 European Commission Directive on Tunnel Safety—The EU has agreements governing road signage, including signage standards for tunnels, through an affiliated group, the European Commission. As a result of the Mont Blanc and Tauern tunnel fires, the commission launched two initiatives. The first initiative was research projects for road tunnel safety. The second was legislation via a 2004 directive that applies to tunnels longer than 5 km (3 mi) on the trans-European road network.

The directive provides the following:

- Assigns responsibility for safety to the road tunnel manager and administrative authority for safety compliance to the local governing authority. For France, this authority is the prefecture. Included in the directive are requirements for safety inspections and a safety officer appointed by the tunnel operator.
- Defines procedures for road tunnel operation. For new road tunnels, these procedures require the tunnel operator to seek permission from an administrative authority during the design and construction phases and before placing the tunnel in operation. Permission also has to be obtained both before and after major changes to a tunnel, and a safety inspection report must be provided every 6 years. These procedures also apply to existing road tunnels, but a timeframe of 10 to 15 years has been granted for compliance. The process for the required safety analysis was not specifically defined, but required that each country have a standard methodology and report to the European Commission. The directive does not require risk analyses for all tunnels.
- Establishes safety measures. Tunnel operators must meet both the requirements of the European Commission Directive on Tunnel Safety and their own national standards.

Integrated Safety Philosophy in the Netherlands—The Dutch integrated approach for tunnel design is being used as a guideline in the Netherlands and can be accessed at *www.tunnelsafety.nl.* Developed in 2001, the guideline will be part of a law scheduled to be discussed in the fall 2005 in the Dutch Parliament and to become effective in 2006 if passed.

In the late 1970s the Netherlands shifted from practical tunnel design to a probabilistic design approach. This approach is largely a result of lessons learned when much of Holland was flooded in 1953. The approach determines the risk in a tunnel based on a quantitative risk analysis that considers probability and likely consequences of a particular type of incident, given a set of predictable safety measures. This work formed the basis for Holland's tunnel design standards.

In the mid-1990s, the probabilistic design approach was questioned. While it gave a level of expected safety, it did not address what happens or should happen when a disaster actually occurs. The scenario analysis, a deterministic approach, considers tunnel emergencies in the design phase. For this method the emergency response plan, incident scenarios, and safety design features are defined and then evaluated. The probabilistic approach and scenario analysis resulted in similar designs.

Several serious tunnel incidents across Europe in the late 1990s to early 2000s and increasing surface land development resulted in pressure to develop a framework in which all safety issues could be described. This integrated safety philosophy provides a structure to solve problems and allows the objective comparison of alternate tunnel designs. It is "integrated" because it was developed in cooperation with all relevant parties. It covers both the construction phase and the operating phase, and it addresses all safety aspects in the tunnel and its immediate environment. It distinguishes between proactive, preventive, preparatory, repressive, and followup measures, and the tasks and responsibilities of all those involved are clearly defined.

Several terms are used in the probabilistic approach to the safety issue, where a large number of incident scenarios are analyzed for probability and associated consequences. The Dutch use the term "risk" to dissociate safety from its emotional association, and differentiate between "external" safety and "internal" safety. External safety is related to the risks of individuals or groups of individuals in the vicinity of a source of danger such as a highway crash. An extra risk is created when the road is underground, producing extra dangers internally. An example is a tunnel fire where motorists are exposed to heat, smoke, toxic fumes, and possibly explosions from which they cannot easily escape. This is referred to as internal safety.

In addition to the probabilistic approach, a limited number of scenarios can be systematically analyzed in more detail. In this case, actual incidents and associated rescue options are examined. The scenario analysis in this deterministic approach includes the concept of self-rescue, in which emergency services have not yet arrived and individuals must rely on themselves to survive the emergency. Of course, other emergency response measures aside from self-rescue are also considered.

A third approach is the ALARA principle. ALARA stands for "As Low As Reasonably Achievable." In this approach, the designer uses common sense to determine where extra safety benefits can be achieved in a practical way at minimum cost.

Project safety can be evaluated using the Safety Chain. The basic structure of this chain is as follows:

- Prevent dangerous situations (proactive).
- In cases where danger cannot be prevented, attempt to decrease the likelihood of an incident and to limit its potential consequences (preventive).
- Should something occur, ensure that measures are in place to provide those present with optimal possibilities to escape (corrective). An often-used term in this situation is "self-rescue" (something occurs, emergency services have not yet arrived, and road users have to help themselves).

- For cases in which emergency response is required, ensure that response measures are as good as possible (repressive).
- Restore the situation to its original condition (followup care).

With the safety philosophy, intervention should occur as high up in this chain as possible to prevent the incident. This philosophy can be used on all types of tunnels, although the details will vary depending on the individual type. An example of its use is the integrated safety plan developed for the Westerschelde Tunnel.

Integrated Safety Plan for the Westerschelde Tunnel—The Westerschelde Tunnel is a 6.62-km (4.11-mi) twin-bore tunnel 60 m (200 ft) maximum below sea level with two lanes each and 12-m (39-ft) cross tunnels every 250 m (820 ft). It crosses the Westerschelde River to connect the southern part of the Zeeland Province to the rest of the Netherlands; the only connection previously was provided by two ferries. Safety measures cost €160 million (US$190 million), or 30 percent of the total €550 million (US$650 million) construction cost.

This project was the first use of an integrated safety plan for a large project. It was jointly developed by the Ministry of Transport, Public Works, and Water Management and the Ministry of the Interior. The integrated safety plan took more than 2 years to develop because of the large number of participants.

The integrated safety plan is divided into the following components:

- A safe work plan based on the Dutch legislation on health and safety at work.
- An incident support plan during the construction activities.
- A traffic management plan for normal traffic management.
- An incident support plan.
- A safe maintenance plan for the operating period.

Each component addresses the safety aspects specific to that plan, the overall safety chain, and the tasks and responsibilities of the relevant parties.

The most significant safety measures in the proactive stage were the following:

- Unidirectional traffic, which means that frontal collisions are virtually impossible and an important element of the crash probability is reduced to zero. Furthermore, good conditions for ventilation are created so that the consequences in the event of a fire are reduced.
- Prohibiting the carriage of certain hazardous substances (e.g., liquid propane gas (LPG) and highly toxic materials). This also eliminates certain types of incidents.

The most significant safety measures in the preventive stage were the following:

- Reversible longitudinal ventilation along the tunnel.
- Carbon monoxide (CO) and visibility monitoring.
- Traffic guidance and monitoring (e.g., CCTV and velocity monitoring).
- Thermal protective lining.
- Communication systems (e.g., intercom, loudspeakers, high-frequency (HF) radio system, telephone).
- Prohibition on truck passing.
- Automatic lighting control system for the transition from daylight into the tunnel.
- Electric power supply with a no-break system.

The most significant safety measures in the corrective and repressive stages were the following:

- Fire detection systems.
- Cross passages every 250 m (820 ft).
- Firefighting systems.
- Ventilation system that starts automatically.
- Disaster plans.
- Clear and straightforward operator instructions.
- Separate service roads to the tunnel entrances and exits for emergency services.

The safe maintenance plan was completed shortly before the opening of the tunnel so that the latest information could be included. It includes descriptions of the various maintenance operations, conditions for safe maintenance, and implementation of the maintenance operations.

TNO believes that this philosophy and the corresponding safety management system guarantee a high level of safety, with the residual risk reduced to an acceptable level.

Special consideration in the overall safety analysis was given to the situation in which an incident forces road users to flee from an affected bore to an unaffected bore. The scenario is as follows:

- The emergency is detected.
- In one single action, the operator does the following:
  - Stops new traffic entering each bore.
  - Closes the left-hand lane of each bore to traffic.
  - Imposes speed restrictions in each bore.
  - Starts the ventilation system of the affected bore.
  - Switches the tunnel lighting to the maximum level.
  - Unlocks the escape doors in both bores (doors are normally locked for security).
  - Activates the lighting of the escape route indicators.
  - Activates the overpressure ventilation of the cross passages.
  - Switches on a special "pedestrians on the road" sign in the unaffected bore.
  - Activates firefighting pumps.
- The emergency is of such nature that road users are instructed to escape to the unaffected bore.
- Road users enter the escape passages and reach the safe bore through the door on the other side.

To avoid road user panic, it was decided to unlock the doors in both bores at the same time. This meant that those escaping to the safe bore might reach it when cars are still passing through it. To increase safety, a traffic information system for the unaffected bore was developed, and the following four options (see figure 10) were considered:

1. Stopping the traffic in the unaffected bore using an "accident" sign and flashing amber lights immediately followed by red lights (sudden stop approach).
2. Stopping the traffic in the unaffected bore using an "accident" sign and lowering the limits from 70 to 50 to 30 km/h (from 40 to 30 to 20 mi/h) and then to red lights (gradual stop approach).
3. Clearing the left lane of the unaffected bore using an "escaping pedestrians" sign and presenting red crosses above the left lane

and imposing a speed limit of 70 km/h (40 mi/h) in the right lane, followed by reducing the speed to 50 km/h (30 mi/h) and then to 30 km/h (20 mi/h) in 10-second intervals (sudden lane-clearing approach).

4. Clearing the left lane of the unaffected bore using an “escaping pedestrians” sign and lane-change arrows and imposing a speed limit of 70 km/h (40 mi/h) in the right lane, followed after 10 seconds by red crosses and 50 km/h (30 mi/h), and followed after another 10 seconds by 30 km/h (20 mi/h) (gradual lane-clearing approach).

These four approaches were tested in a simulator. The major conclusions from this test were that lane clearing proceeds smoothly but stopping traffic does not, and that the gradual lane clearing approach is most compatible with the signaling used outside the tunnel and most effectively clears the unaffected bore for emergency services. Individuals in the test said that the gradual lane clearing was good because they recognized the arrow from its other uses; this shows that users do not pay attention to red crosses or lights, but do pay attention to established signage. If the evacuation is successful, the situation is considered satisfactory because human life has a higher value than cars and facilities.

Copenhagen Metro Safety Approach in Denmark—The design process and criteria for safety-related features in the Copenhagen Metro are based on European standards and modern European installations. It begins with the concept and proceeds to system

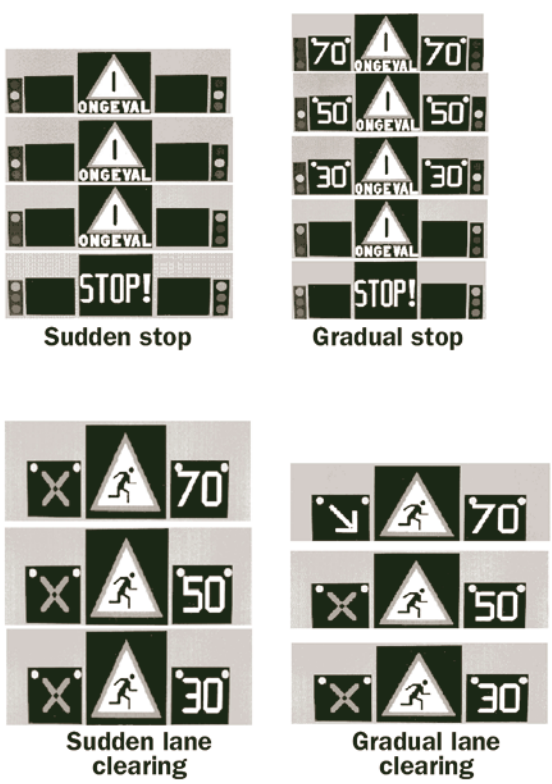


Figure 10. *Scenarios for evacuation safety in tunnels: sudden stop, gradual stop, sudden lane clearing, and gradual lane clearing. (Dutch Ministry)*

definition and application conditions, to risk analysis (which may be repeated at several stages of the life cycle, depending on modification and retrofit), to system requirements, to apportionment of system requirements, to design and implementation. The process further considers manufacture, installation, system validation (including safety acceptance and commissioning), system acceptance, operation and maintenance, performance monitoring and modification/retrofit, and decommissioning and disposal.

This is the first project of this complexity in Danish railway history, and at the start of the project there was no established set of standards. Subsequently, many standards from a variety of sources were adopted for the project. The main ones are mentioned here. The German code, BOStraB, was used as the overall code and standard framework. Compliance with Danish building regulations, Eurocode EN50126, and NFPA 130 (as a supplement to BOStraB) were required. Vulnerability assessment was done by the consultants as part of the design.

The Metro safety requirements were defined by the employer in agreement with the Ministry of Traffic and encompass quantitative risk acceptance criteria, norm-based requirements, and contributions by emergency services. The Metro risk acceptance criteria must have the same level of safety as other systems in Europe. Statistics from Skytrain, Vancouver, VAL, LuL, DSB S-tog, etc., were used for analysis because they were believed to be similar systems. A hazard identification and analysis document was used to develop design criteria. As risk changes, these assumptions must be revisited occasionally and possible new countermeasures introduced.

The ventilation system was designed to provide redundant airflow paths to provide for the loss of a vent shaft. Ventilation initially works automatically but has a manual override/backup.

Cut-and-cover sections use stainless steel mesh to reinforce and minimize spalling. Strain in the lining and corrosion and lining distortion are all monitored by instrumentation and imbedded sensors. Fire protection is provided by a sacrificial stainless steel-reinforced protective lining inside the tunnel.

The codes take accidental loads into account (e.g., derailment and fires). There are no specific codes for concrete lining damage, flooding, or blast design. The level of blast is chosen by the owner. Sweden limits the amount of explosive goods that can be taken on one train and will not allow dangerous cars during the day (on a case-by-case basis).

The following are some of the safety features in the system:

- Sensors to address traditional hazards, including a sophisticated system for fire detection.
- Passenger information systems.
- Remote cameras to watch stations and cars.
- A redundant control system (though in the same building).
- An obstacle detection device to prevent passengers from getting hit by trains.
- Intrusion detection devices.

Emergency drills are planned with emergency services to test and verify response plans. Mutual aid agreements exist for the region for response, but interoperability of communications equipment does not exist.

Rambøll Risk-Management Approach to Design in Denmark—Rambøll uses risk management as the basic approach to designing railway infrastructure safety systems. The European community establishes standards for a process to perform risk analysis of safety systems. The owner determines the design criteria to be used. Rambøll develops the risk analysis by breaking the project into its components and presenting them in matrix format. It develops a mathematical model of the system and uses the results to provide the client with the information to assess the various options on the basis of cost versus risk. An example of the type of input for the risk analysis is the modeling for a fire on a subway train. Computational fluid dynamics (CFD) was used to evaluate the spread of smoke versus time. All materials used in the train construction were incorporated in this model, but it did not incorporate fire suppression.

Another example is the safety analysis for the design of the Copenhagen Metro in the 1990s. The focus of the analysis was on train-related passenger safety and structural reliability. The analysts did not focus on an explosion in the tunnel in developing the design because they believed explosive forces could not be designed for cost effectively.

Rambøll also did design work on the Oresund Link tunnel. The design was based on European codes rather than specific codes from either Denmark or Sweden, as a way of being neutral. The basic approach was to look at bridge design guidance and adapt appropriate provisions to tunnel design. Specific design requirements were developed as needed where no guidance was available. For fire design, the company developed a project-specific level of risk for different scenarios. This led to the installation of fireproofing liner to protect the concrete from spalling.

Future trends in risk analysis include developing models that incorporate health, safety, environmental factors, and quality into a single model. An increased focus on terrorism is also a future trend, as is the protocol for facility inspection based on risk analysis.

Citytunnel Safety Approach in Sweden—The safety policy for Citytunnel is that it will meet strict requirements on safety for people, properties, and the environment. High accessibility and safety are important aspects for increased use of railway traffic. A high level of safety is achieved by attaching safety to planning, design, and construction and getting continuous feedback from other interested parties.

The four ruling laws that govern the design and construction are the Planning and Building Act, the Swedish Environmental Code, the Railway Construction Act, and the law on technical requirements for buildings and plant structures. Checks are made through risk analyses; meetings with the fire brigade, police, and others to discuss safety problems and solutions; scenario staging; and annual reports to authorities on current and planned safety measures. However, no specific laws or regulations govern underground railroad operations.

The project safety objectives were to conform to the methodology and acceptance criteria contained in BVH585.30. This meant that the tunnel operation was to be as safe as open, at-grade track operation from derailment, collision, fire, etc. The stations were required to be as safe as any other building used for public assembly; building codes are used even though the existing building regulations were not designed to apply to tunnels. The evacuation goal was to have safe evacuation without assistance. The safety concept included an emergency evacuation procedure, a rescue operation procedure, a risk analysis, and safety systems. Highlights for specific criteria that resulted include the following:

- Trains should be evacuated at stations or outside the tunnel if possible, with emergency braking blocked out when in the tunnels.
- Only passenger trains were allowed in the tunnel.
- Scenario designs through tabletop exercises were conducted.
- Separate fire curves were developed for rolling stock and structures.
- CFD fire calculations were performed.
- Safety refuge staircases in stations should have positive air pressure.

Normal ventilation is caused by train movement. The jet fans are used only in an emergency to control smoke and fire. The fans are along the entire system and have pressure relief vents to reduce wind on the platform to an acceptable level. The stations have chimneys to release smoke.

There are also requirements for rescue services and environmental regulations. Many of these building code requirements do not necessarily comport with specific considerations for tunnels. The government is working with the planning and building authority, fire brigade, and others to determine whether special tunnel regulations are needed.

Citytunnel met with the fire brigade and relied on the Eureka tests and the Swedish National Testing and Research Institute (SP) for guidance. From the safety concept, Citytunnel evaluated other work, including fire simulations, evacuation simulations, and crash safety evaluations for tunnels and stations to develop risk analyses. From this it developed Safety in Technical Systems (SITS).

Fire brigade intervention should be possible for certain, but not all, scenarios. The 15-MW fire is the standard because the concern is that the fire brigade would be able to extinguish only relatively small fires. Citytunnel developed a matrix of responsibilities and calculated fire evacuation times. From the analysis of the matrix, it was determined that by the time the fire is at the 50-MW stage, the fire should be left to burn, and the response should emphasize search and rescue.

Fire smoke simulations were done for fires up to 15 MW for the performance-based design. Time-temperature curves and temperature resistance requirements were developed with help from SP. Researchers simulated fires and evaluated various evacuation patterns. The current risk analysis for passengers being evacuated is an acceptance matrix from the rail authority, and Citytunnel is replacing the matrix with a new frequency curve.

This work resulted in identifying many safety systems. To limit disruption and increase safety, Citytunnel installed various equipment (e.g., CCTV) for the full length of the tunnel to allow the control center to determine whether a disruption is required. Discussion is ongoing on the use of CCTV, however, and some do not favor camera use. Staircases are enclosed with fire-resistant glass and designed for over-pressure. The fire brigade has access routes that are separate from the evacuation route.

General requirements are that the evacuation time determines the maximum capacity needed, with 60-minute functionality and

120 minutes for rescue operations. When feasible, emergency systems should be combined with normal operating functions. Automatic operation is recommended since many scenarios are too complicated for manual operations.

Standards for Tunnel Safety in France—CETU officials explained that France had been working on technical standards for new tunnels and the standards existed in draft form in 1999. As a result of the tunnel fires in Mont Blanc and Tauern (Austria) in 1999, the French launched two initiatives. The first was a 3-month joint French-Italian investigation and report on the Mont Blanc Tunnel fire. The second initiative was a safety check of the 40 road tunnels longer than 1 km (3,280 ft), with general recommendations for safety of all tunnels and specific recommendations for each one that could go as far as closing the tunnel completely or closing the tunnel to heavy vehicle traffic.

Also, new regulations were issued in 2000 that included technical aspects covering minimum safety standards, operations (new to tunnel standards), and safety procedures for both new and existing road tunnels. These regulations as well as all subsequent French regulations cover road tunnels longer than 300 m (984 ft).

In addition, a circular provides enforcement power for all government-owned tunnels, requiring owners and operators to get authorization from the local governing authority (prefecture) to operate existing road tunnels. Owners must get advice from the prefecture to operate existing tunnels. The prefecture uses a National Evaluation Committee for technical advice. Determining safe operation is based on a safety analysis of each tunnel consisting of a review of likely scenarios, an evaluation in detail of three or four specific scenarios for safety risk and mitigation measures, and a report to the prefecture on safety. This safety analysis is called "specific hazard investigation" and has been incorporated in the European Directive 2004/54/EC (see below).

A law on safety of transport infrastructures and systems was passed in 2002 and made applicable in 2005 for nongovernment-owned road tunnels. The law made it compulsory to carry out a safety examination every 6 years, have new road tunnels adhere to the standards, and have owners of existing road tunnels set the goal to achieve compliance. This does not imply applying strictly recommended safety measures; different measures are acceptable as long as the same level of safety is achieved.

The French method for tunnel safety risk analysis is basically the aforementioned deterministic specific hazard investigation involving scenarios and mitigations. A different risk analysis method is used to decide whether dangerous goods should be allowed in a tunnel. It uses the Quantitative Risk Assessment (QRA) model jointly developed by the Organization for Economic Cooperation and Development (OECD) and the World Road Association (PIARC), and sold by the latter. As a first step, the average number of fatalities per year in the tunnel due to dangerous goods incidents is calculated, supposing all dangerous goods are allowed. If this figure is below 10-3 fatalities per year, dangerous goods are not considered significant in terms of risk, and the decision is based on other criteria. If not, the method employed involves a quantitative analysis to calculate risk for travel routes through the tunnel as well as alternate travel routes.

The risks are then compared for the various routes. The first criterion used is the average number of fatalities per year on each route:

- If risk is 10 times greater, choose a lower risk route.
- If risk is between 3 and 10 times greater, then perform a sensitivity analysis to check whether risk will remain at least 3 times greater under all hypotheses.
- If risk is 3 times or less, then look at other risk indicators and other factors to determine the travel route.

Existing road signs banning all or part of dangerous cargoes are used for enforcement. A new European classification is under preparation and should make it possible to differentiate among five groupings of dangerous goods labeled A to E. In a very few tunnels, the toll gate facilities can be used to stop the passage of hazardous and dangerous goods. Regulations can range from allowing all or some categories of dangerous goods to pass through, to pass through under prescribed circumstances, or not to pass through under any circumstance.

Tunnel Design Standards in Germany—Germany had standard regulations for the design of new tunnels, entitled RABT, that had been updated in the 1980s. New standards were published in 2004 after the Mont Blanc and Tauern tunnel fires. The new standards raised the design fire scenario from 15 to 20 MW to 30 MW, with provision for 50 MW for tunnels with a high number of heavy vehicles (e.g., 4,000 per day). The new standards are compulsory for new federal roads and for state and urban road tunnels using federal funds. Germany will spend €600 million (US$709 million) over 10 years to upgrade tunnels to the new standards.

Tunnel Design Standards in Switzerland—Swiss tunnel design codes adopted in 2004 are now available in English. The set is produced by the Swiss Standards Association (SIA). The previous edition, *SIA 198—Underground Construction* (1993), covered regulations on execution, with design mentioned only briefly. The current codes are directed toward design engineers, owners, operators, and those involved in site supervision and execution of construction works.

SIA 197—Design of Tunnels, Basic Principles covers the basic principles to take into consideration in designing traffic tunnels (railways or roads), including the aspects of safety and environmental impact. It also includes the regulations dealing with the design of an underground structure following the SIA structural codes. The special features to consider in the case of road and rail tunnels are covered in the two specialized codes, *SIA 197/1—Design of Tunnels, Railway Tunnels and SIA 197/2—Design of Tunnels, Road Tunnels.* The three copyrighted documents, published by SIA, and are available by writing PO Box CH–8039, Zurich, Switzerland.

Design Issues in Switzerland—The tunnel designer needs to design the tunnel for the next generation's tunnel managers. Systems should provide for responses that are as simple as possible.

The primary purpose of ventilation is to support self-rescue and aided rescue within 8 minutes (see figure 11). Influences on the design fire include buoyancy, critical velocity, and smoke production. For tunnels with two tubes, an escape passage should be provided every 300 m (980 ft) between tubes and every third should allow for access by emergency vehicles. For tunnels with a single tube, an escape gallery leading to the open should be provided every 500 m (1,640 ft) at 1 percent roadway grades to every 300 m (980 ft) at 5 percent and greater roadway grades. A parallel safety gallery should be provided for long tunnels. These requirements are now part of the Swiss standards. The new directive sets a standard and defines minimal requirements. The main goal of the tunnel ventilation requirements is the rapid control of the longitudinal flow. Ventilation and escape routes must be coordinated into one concept.

Current standards require an automatic linear temperature detection system (LTDS) video including incident detection. Fundamental requirements are detection of a fire within 1 minute, start of ventilation within 1 minute, and system reaction within 3 minutes. Requirements for smoke detection are to locate hot and cold smoke within 60 seconds and within 100 m (330 ft), or possibly up to 300 m (980 ft), depending on type of traffic, with a very low rate of false alarms. Measurable items include smoke (opacity), CO, video optical detection, linear temperature, and local temperature.

Fire in tunnels always means smoke. Experiences from fires greater than 30 MW, such as in the Gotthard Tunnel, indicate opacity much greater than reported by the LTDS. For the 2004 Baregg Tunnel fire, the LTDS took 7 minutes to detect the fire.

Design Issues in Plabutsch Tunnel in Austria—Lighting improvements include 25 percent increased efficiency in portal zones and traffic-dependent adjustment of the illumination level. Temperature resistance of the lamp is 250 °C (480 °F) for over 1 hour. "Awareness rising zones" in special areas of the tunnel provide up to 10 times normal illumination. Emergency niches and awareness rising zones are provided with emergency phones, water supply, and other safety equipment.

Escape Route Signs

The Netherlands—New escape route signing to enhance self-rescue was developed for the Dutch Ministry by TNO. The key to enhancing self-rescue is to let motorists know what to do and how to do it, and to emphasize that they need to leave the event area as soon as possible.

Simulation studies have indicated the following:

- People are passive and do not take action.
- People miss the emergency doors in the smoke.
- People become disoriented along the wall or road surface.
- Uncertainty about what to do is common.

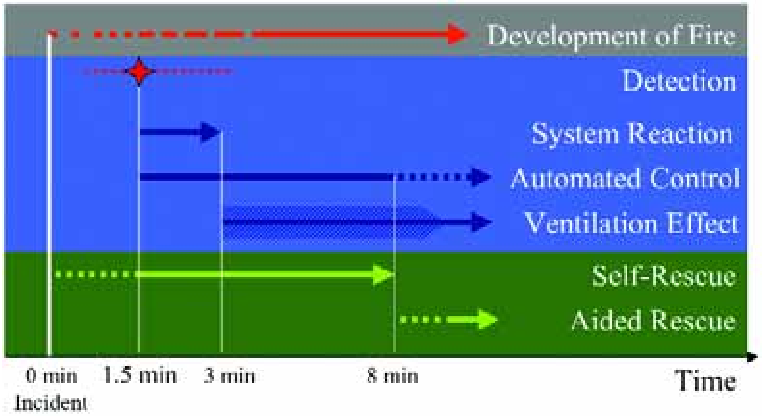


Figure 11. *Ventilation to support self and aided rescue (FEDRO).*

- Sound support (where people are guided by sound to an evacuation route) is typically poor.

To assist users, TNO did research to make signs that are visible, clear, and logical. Now the Netherlands has a sign standard that consists of a pictogram with a white running figure on a green background. Signs are installed on and near the escape doors. See figure 12. In case of an emergency, LED lighting at the escape doors increases the visibility of the escape route. Pictograms with white lettering on a green background showing the direction and distance to the escape doors are required on walls every 25 m (82 ft). Much discussion occurred on which languages to use for the signs; it was decided to use Dutch and English. Another idea, which has become standard, is to put arrows on the pavement at escape doors. The arrows are raised so they can be felt and laminated for long-term wear.

The standard also includes sound. The Dutch initially used a chirping alarm as an effective audible device. It was audible and locatable, but frightening. In early 2005 TNO developed an enhanced system with the addition of spoken words in Dutch and English to give directions. The revised sound-voice combination to help motorists locate the escape doors is now the standard in the Netherlands.

Mont Blanc Tunnel Between France and Italy—As designated elsewhere in Europe, refuge room doors are green with prominent display of white running figures, and similar signs are

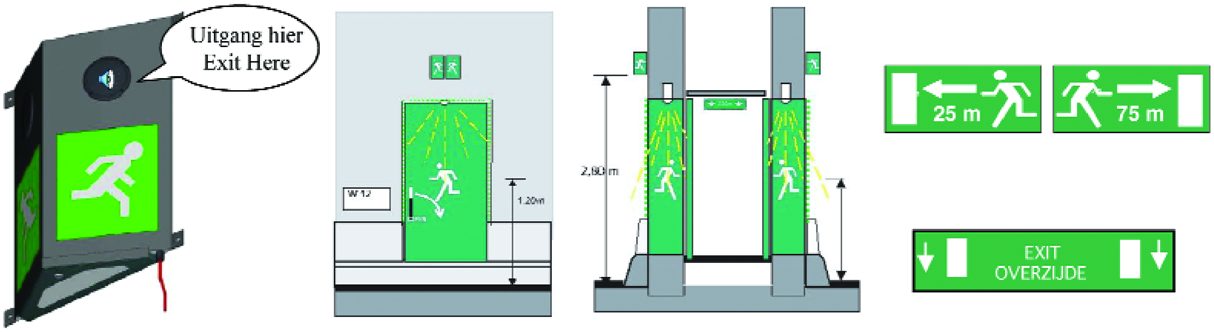


Figure 12. *Sensory combination for location of escape doors. (Dutch Ministry).*

installed along the tunnel length to show the direction and distance to the refuge rooms (see figure 13).

Plabutsch Tunnel in Austria—The tunnel has fully automatic escape route signals with selective display of escape direction determined by the emergency.

LED Lights

Grilstad Tunnel in Norway—Several years ago, the Norwegian Public Roads Administration hired SINTEF to study the use of LED lights in the Grilstad Tunnel near Trondheim. The tunnel, 700 m (2,300 ft) long, consists of two tubes with two unidirectional lanes per tube and has an average of 10,000 vehicles per day in each direction. Its posted speed is 80 km/h (50 mi/h). It has ordinary roof lighting and LED lights at 20-m (66-ft) spacing at each outside edge of roadway (see figure 14) and 15 m (49 ft) at both ends. The objective of the project was to obtain driver opinions on security, safety, and comfort and to study driver behavior as a result of different light intensities.

A week-long testing program was conducted in which LED-light intensity was varied at different times of the day, but with 100 percent ordinary lighting on the roof. Driver opinions were solicited to determine lighting level and spacing adequacy. The most satisfying LED-light level was found to be 47 percent intensity with 100 percent ordinary roof lighting. The normal 100 percent LED-light level was perceived to have too much glare.

Figure 13. *Examples from the Mont Blanc Tunnel. Top: tunnel escape route. Bottom: tunnel escape route sign.*

Driving behavior under various lighting levels was also evaluated. Speed was not significantly impacted. The LED lighting, however, did influence the vehicle's lateral position, with optimum position at 100 percent LED lighting. Drivers felt safer and moved closer to the shoulder as the LED intensity increased.

A fire drill was conducted in the tunnel before it was opened, and the fire department found the LED lighting useful for evacuation. LED lights are favored in Norway because in the winter, reflective striping becomes covered with snow spray within 2 weeks while LED lighting remains visible.

Escape Doors in the Netherlands—In the Netherlands, the use of LED-lighted escape doors has become the standard (see figure 13) because officials believe this makes escape routes more visible in an emergency. Strobe lighting was tested but is not used because flashing pathway lights can be confused with the lights used on first-responder vehicles.

Mont Blanc Tunnel Between France and Italy—LED lights were installed along the edge of the tunnel at regular intervals of about 10 m (33 ft) to clearly identify the edge of the roadway. The majority of these lights were a highly visible yellow color. Spaced among the yellow lights at 150-m (490-ft) intervals were blue lights. See figure 15. Motorists are instructed through formal (for truck and bus drivers) and informal driver education to keep a safe distance between them and the vehicle in front, and that distance is indicated by the spacing of the blue lights. This visual cue is more reliable than asking motorists to establish distance between vehicles using speed-based guidelines.

Design Fire Size

European countries differ on their design fire size (e.g., Sweden uses 15 MW and Austria and Switzerland use 30 MW). The 2004 German standards raised the design fire scenario from 15 to 20 MW to 30 MW, with provision for 50 MW for tunnels with a high number of heavy vehicles (e.g., 4,000 per day).

For the design fire scenarios in the Netherlands, TNO did tests to develop time-temperature curves for fires that last 2 hours. As a result, the Dutch standard now is for every tunnel in the basic road network to resist a 2-hour fire at 1,350 °C (2,460 °F). TNO found fires as high as 1,400 °C (2,550 °F).

Sweden uses a design fire of 15 MW. SP reports that large fires from semi-trucks and tankers can cause another truck to ignite as far away as 100 m (328 ft). SP research shows that the fire brigade cannot handle large semi-truck or tanker fires, and that for high-megawatt levels, they are considered "fire zones" in which no one can survive.

In Switzerland, a design fire of 30 MW represents a loaded truck. Temperature rise is 65 degrees Kelvin over a distance of 800 m (2,600 ft) within 10 seconds. Influences on the design fire include buoyancy, critical velocity, and smoke production.

A 100-MW design fire is recommended in the annex to NFPA 502. Fires greater than 100 MW have been documented with heavy goods vehicles.

Fire Suppression Systems

The UPTUN project is putting a large amount of effort into developing methods to achieve fire suppression in tunnels. Fire suppression systems now vary in European countries.

Norway—SINTEF NBL has the capacity to create full-size mockups to test fire suppression. Testing of water mist systems has produced good results but requires that the system have the proper design to work properly. Water is good because it absorbs heat well. Full-scale testing is required.

Fixed water-based fire suppression systems for tunnels are found in very few countries. Japan uses sprinkler systems, typically 6 liters per square meter per minute. Water-based fire suppression systems have the following potential advantages:

- Cool the tunnel around the fire.
- Suppress the fire, significantly lowering the rate of heat release.
- Greatly reduce smoke.
- Reduce toxicity.
- Prevent spread of the fire.
- Keep temperatures in structural members from reaching the elevated temperatures that cause permanent damage.

Water mist fire suppression systems (e.g., 2 liters per square meter per minute) reduce the fires to 30 to 60 percent of their original size but do not put them out; the intent is to keep the smoke and heat down. These fire suppression systems have high installation and maintenance costs.

The Netherlands—The Dutch Ministry has a pilot project using a compressed air foam system in the Roertunnel on the A73 motorway in the Netherlands. The tunnel will have this additional safety installation because traffic includes liquid propane gas (LPG) tankers. The Dutch believe that in this typical application (LPG tankers), compressed air foam is better than a sprinkler system, although more expensive.

Sweden—The September 2003 Runehamar Tunnel fire tests of semi-trailer loads were conducted with a fire size up to 200 MW. SP observed that if users are expected to stay in their vehicles, it is best to use fire suppression. People have a high probability of escape if fire suppression is used to keep the fire below 30 MW. Human behavior studies have shown that people tend to stay in their vehicles much longer than they should.

If suppression systems are installed in high-traffic tunnels, SP recommends that they be simple and robust with an emphasis on both performance and maintenance.

Figure 14. *LED lights on roadway edges in the Grilstad Tunnel. (SINTEF).*

Figure 15. *LED lights in the Mont Blanc Tunnel: yellow for edge delineation and blue for vehicle spacing.*

France—CETU discussed the use of water deluge systems, either the mist or sprinkler type, as a means to contain fire and improve safe evacuation. CETU officials indicated that they are considering this and believe that more study is required.

Germany—STUVA provided information on Japanese practice, where water suppression is used for tunnels over 10 km (6 mi) long or over 3 km (2 mi) with high use. However, STUVA noted that there are issues with water suppression. Current practice assumes that well-designed ventilation systems without suppression are best, until further research shows otherwise. Water systems can compromise the stratified smoke layer and in some cases make evacuation more difficult. STUVA indicated that while some advocate mist systems, many are awaiting the results of further research from studies by the UPTUN and L-surF projects.

Austria—The purpose of water-based fire suppression systems is to reduce the heat load. It is also easier to breathe moist smoke. Another advantage of using a sprinkler system is that the chance of flashover from one vehicle to another is reduced. Structural damage from a fire is also typically less when a water-based fire suppression system is used.

However, water-based fire suppression systems destroy the smoke layering, and smoke layering can allow users adequate time to evacuate in a fire incident. It is desirable to keep the smoke layering system as long as needed to allow everyone to evacuate. The smoke would need to be reduced by 95 percent to have adequate visibility after the smoke layering is destroyed.

The use of water sprinklers is a big debate in PIARC. Japan and Australia mandated use of sprinkler systems. Europe does not have a regulation that requires a water system. Austria has concerns about the use of sprinklers in tunnels, and currently does not allow them to be used automatically. Austria has two tunnels with sprinkler systems: one in a very short tunnel with manual activation only, and a second one in a 5.4-km (3.4-mi) long tunnel that is in the installation phase. Austrian regulations say that the operator must evaluate the situation. If there is no smoke layering, then a water mist system can be used; if there is layering, the operator must wait to use the water mist system until everyone has evacuated. The decision is based on the air speed and the sprinkler system. The sprinkler must be above the fire to be effective. A water-based fire suppression system is allowed in the first 10 minutes only if everyone has evacuated the tunnel. An Austrian guideline defines the minimum requirement of fire suppression systems and the operation procedures for the ventilation.

Water mist has the advantage that small droplets reduce heat better, but water mist also reduces smoke layering and visibility. An advantage of water mist over sprinklers is that it uses less water. One disadvantage is that the water mist system can freeze (heating has to be provided at the portal regions). A problem in the Alps is that water may not be available in the required amount and it is difficult to bring water to the site, store it, and distribute it. As a result, Austrians have little to no experience with water-based fire suppression systems.

Ventilation Systems

Over the recent past in Europe, interest in fresh air and the environmental impacts of ventilation has decreased, but interest in safety has increased as a result of the many tunnel fires that have occurred.

Currently, ventilation design criteria vary throughout Europe and elsewhere. PIARC is working to develop a harmonized approach to tunnel ventilation. Under PIARC's guidelines (now a working document, but scheduled to be converted into guidelines in 2007), for a tunnel with unidirectional traffic flow, ventilation airspeed is maintained at between 1.5 to 2 meters per second (m/s) (4.9 to 6.5 feet per second (ft/s)) in the same direction as traffic. For bidirectional traffic, air speed is maintained at 1 to 1.5 m/s (3 to 4.9 ft/s) in the same direction of travel except to within 500 m (1,640 ft) of the portal, depending on the evacuation procedure.

In Europe ventilation is controlled in normal mode mainly by opacity (the spacing of the optical sensors varies). In incident mode, various detection systems are used. Heat detection (either by linear heat sensors or laser systems) provides the main information. Some countries include opacity, with optical sensors in very short intervals of 100 to 200 m (328 to 656 ft). CCTV has proven to give very fast detection. Because the rate of wrong signals is still very high, however, this system is used mainly for information (alert) and the operator has to confirm and trigger the fire alarm manually.

Sweden—SP is experimenting with ventilation systems to control smoke and remove the heat to prevent the fire from spreading.

Sweden does not recommend installing water sprinklers in tunnels. SP speculated that in 10 years Europe may go to transverse ventilation with water spray, rather than longitudinal ventilation, to handle the bigger fires that can result from high congestion. An exhaust vent stack may be a better system than blowing smoke longitudinally throughout the tunnel; a water spray could be used in the duct work to keep it cool.

Passenger rail cars burn at 10 to 35 MW. If the windows break or fall out or if the doors are left open, the fire is ventilated and will burn faster and hotter. To control smoke and prevent the fire from spreading from such occurrences, ventilation from both sides is needed.

The September 2003 Runehamar Tunnel fire tests of semi-trailer loads had fire size up to 200 MW. Researchers observed that if the expectation is that the users will evacuate immediately, the fans should be turned on to full power. The smoke level rises very rapidly, and in 5 minutes the area is completely engulfed, providing very little time to escape (as little as 1 or 2 minutes).

Mont Blanc Tunnel Between France and Italy—The Mont Blanc Tunnel has semitransverse ventilation, with air pushed into the tunnel. Eight fresh air longitudinal ducts are under the roadway, four on each end to push air. The first duct pushes air the first 1,500 m (4,900 ft), the second air duct pushes air the next 1,500 m (4,900 ft), and this pattern continues to the tunnel center. The 76 jet fans and 20 wind meters in the tunnel provide constant air velocity in the tunnel. An air speed of 8 m/s (26 ft/s) is the maximum velocity permitted at the exit portals. A display shows the air speed inside the tunnel. In normal operations, the air flow curve is a straight line and the point of zero velocity is at the approximate center of the tunnel. If a fire occurs in the tunnel, the operator moves the point of zero velocity to the fire location, and seven dampers at the crown of the tunnel open to extract smoke. Changes in barometric pressure can move the zero-velocity point outside the tunnel entirely. In severe conditions, the zero-velocity point cannot be managed and the tunnel is closed.

Gotthard Tunnel in Switzerland—The original ventilation was provided by four shafts in the mountain and two at the portals. Fresh air is supplied through an overhead gallery on the left side of the tunnel roof to ducts in the lower part of the tunnel walls. Ducts are on the same side as the refuge rooms, which are located every 250 m (820 ft). Exhaust is provided on the right gallery in the roof. The ventilation design is transverse.

Traffic type (density and volume) will drive the choice of the system (see *Fire and Smoke Control in Road Tunnels,* PIARC 05–05–B). The basic type is longitudinally ventilated with jet fans, quite common in shorter tunnels. Most new tunnels longer than 2 km (1.2 mi) use systems with controllable extraction, with or without extraction ducts, and with air galleries and ducts.

The old concept was vertical smoke extraction. The idea was to add fresh air from below from the secondary ducts and extract the smoke through the ceiling ducts. Air was uniformly applied from the tunnel floor to the ceiling to force smoke out. The fear in the past was that it would be too dangerous if the wrong damper were opened. Advancements have allowed the use of dampers in newer systems to allow local smoke extraction through local air pressure adjustment. With such a damper system, an air quantity of up to three times the tunnel cross section can be extracted at a rate of 1.5 m^2/s (16 ft^2/s).

Loetschberg Tunnel in Switzerland—A ventilation system is installed in the Loetschberg Tunnel, although this is a new practice for rail tunnels in Switzerland. The system has a maximum flow capacity of 200 m^3/s to enable the system to maintain a higher pressure in the escape/rescue tunnels than in the main tunnels and keep escape routes smoke free. The ventilation is mainly provided for the emergency stop stations inside the tunnel.

Austria—Expected response time to a tunnel fire for fire brigades is 10 minutes. The expected self-rescue time is also the first 10 minutes after the event. During this time, tunnel operators in Austria decrease the ventilation velocity to a maximum of 1.5 m/s (4.9 ft/s) to facilitate the possibility of self-rescue in tunnels with bidirectional traffic. In tunnels with unidirectional traffic, the air speed in the tunnel is set at 2 m/s (6.5 ft/s). The ventilation procedure in incident cases runs on a controlled mode that is fully automatic. After the fire brigade approaches, the ventilation strategy may be changed on the brigade's advice.

All long Austrian tunnels, those more than 5 km (3 mi) are transverse ventilated except one. Transverse ventilation is now required for tunnels longer than 3 km (2 mi).

Plabutsch Tunnel in Austria—In an incident case, the extraction capacity of the ventilation is 120 m^3/s. Smoke is extracted through one open damper with a cross section of 12 m^2 (130 ft^2). The damper closest to the fire location is opened (depending on wind direction at incident detection). The smoke/airflow inside the tunnel is controlled so that in unidirectional traffic two-thirds of the volume comes from the incident side, while one-third comes from the opposite direction. In bidirectional traffic mode, the split is 50 percent from each side of the open damper. The volume flows are controlled by a closed loop proportional-integral-derivative (PID) controller.

Adjustable exhaust air dampers have an open cross section up to 12 m^2 (130 ft^2) and are located every 50 to 100 m (164 to 328 ft). During an incident, one to three dampers are opened. During normal operations, the open section of the dampers is enough to maintain uniform air flow at full load. The system is designed as a closed loop to ensure backup in the event of a fan failure.

Fan specifications include volume flow of approximately 200 m^3/s per 2-km (1.2-mi) ventilated section, a power requirement of 450 kilowatts (kW), fans resistant up to 400 °C (750 °F) over 2 hours, and fully adjustable blade angles.

Air Curtain

SINTEF NBL is conducting research on air curtains. Air flow of 1 m/s (3 ft/s) is typically required to escape smoke. Installing an air curtain enables a small flow of injected air to redirect the movement of smoke away from the escape pathway. With an air curtain, the smoke can be stopped by an air velocity of 0.25 m/s (0.82 ft/s), one-quarter the typical required velocity (see figure 16).

An air curtain is to be tested in the Oslo central subway station Stortinget in the near future to determine its effectiveness. The testing will be done in conjunction with a fire created for the fire department to do its training. Air curtains will be installed about 2 m (6.6 ft) from the entrance of each escape route. The strategy when

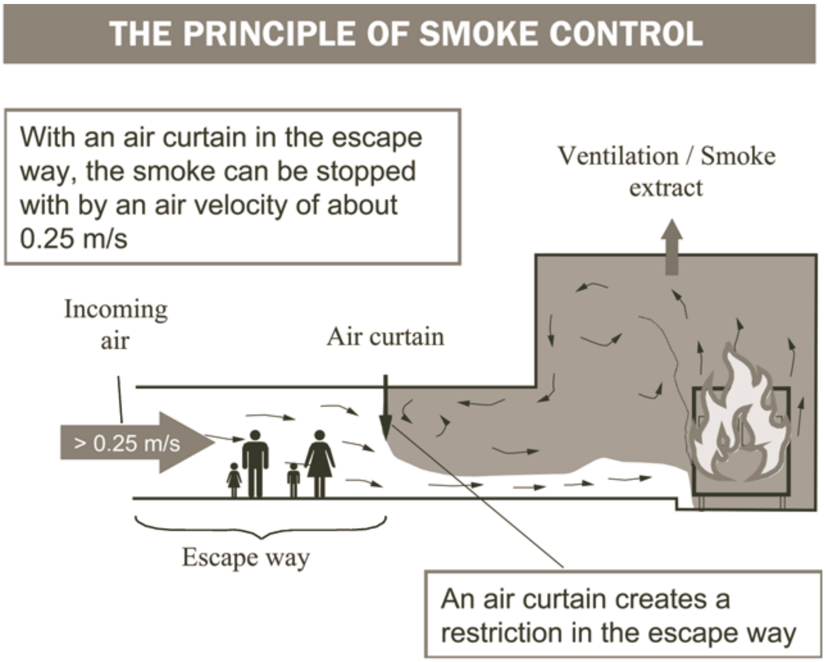


Figure 16. *Air curtain for smoke control in tunnels. (SINTEF NBL)*

a fire occurs is to push one button to initiate automatic emergency response (e.g., extract fans go at maximum speed and air curtains are activated). The reason for using an air curtain rather than a physical barrier is to avoid interfering with people leaving and the fire brigade entering. First the physical barrier is made as low as possible from the ceiling, and then an air curtain is installed to produce a lower air barrier. The first test, scheduled for the end of 2005, will include computational aerodynamic analysis and an oil fire. SINTEF NBL is continuing its air curtain research and plans future testing.

Air curtains may be more appropriate for rail tunnel stations than for the main tunnels, since a closed system with doors in the tunnel where trains enter and exit the station is required for an air curtain to work. The concern is that the doors may accidentally deploy and trains could hit them.

Incident Management

The management of incidents to reduce their duration and impact is a priority for the European countries the scan team visited. These countries have undertaken a variety of activities to effectively manage incidents in tunnels by reducing the time to detect and verify that an incident has occurred, by providing the appropriate response, and by safely clearing the incident while managing traffic flow.

SINTEF in Norway

SINTEF described the Norwegian evacuation strategies for road tunnels. These strategies focus on issues from the recent Mont Blanc, Tauern, and Gotthard tunnel fires. In addition, in London in 1987 an event occurred at King's Cross Rail Station that contributed additional data. A modest fire in an escalator developed into a disaster in which 31 people died. Norway has had several tunnel fires in the past few years without loss of life from fire.

In Norway, single-tube tunnels with two-way traffic typically have natural ventilation. In general, portals are the only possible evacuation directions. If on the wrong side of a tunnel fire, a motorist's only chance is to turn the car around and leave. However, airflow direction may dictate the direction of evacuation.

A frequent problem is that motorists do not recognize the seriousness of a fire; they are worried about possessions and make bad decisions on what to do. The high-traffic tunnels in Oslo and Bergen have systems that can override vehicle radios, but radios must be turned on to receive the messages. A question has arisen on whether more information would increase user anxiety about tunnels. Simulations also raise the question of whether people follow posted instructions or a leader.

The Norwegian crisis management procedure for tunnels is to immediately close all tubes when a crash occurs. Users at the incident location must decide whether to sound the alarm, provide first aid, assist in fighting the fire, leave the car and evacuate on foot, or evacuate by car. Rescue personnel must find their way to the right tunnel entrance. Drivers outside the tunnel must find an alternate route. For all events, motorists in the tunnel are their own first rescuers, and self-rescue provides the most effective evacuation strategy. To be able to rescue themselves, motorists need to know the location of emergency exits and should be guided to the direction of the fresh air supply. Preparedness plans should incorporate these considerations.

Copenhagen Metro in Denmark

The overall safety description for the Copenhagen Metro includes planning, heat load calculations and simulations, laws and regulations, and escape route planning below and above the ground. Detailed discussions with emergency professionals and tabletop exercises have taken place to evaluate plans and provide training. Protocol is that the transit system investigates, determines the emergency, and then sends the alarm. Police are the overall incident commanders.

Additional ventilation is provided by louvers in station ceilings that are tied to the ventilation system and can be opened in an emergency. Counterterrorism and threat support are provided by police; weapons of mass destruction (WMD) plans are also being developed. Emergency rescue equipment is pre-positioned at stations; weather services provide warnings where necessary. Fire detectors, smoke detectors, and CCTV are in place. Emergency recovery plans are in place for terrorist events, tunnel collapse, crashes, and removal of failed vehicles by tow, rescue train, or automatic operation. The target detection time is less than a minute for a failed or stranded train, with a maximum 20-minute service interruption. The target response time is 5 to 7 minutes from the time an incident is reported until the response team is onsite. Fencing is provided for access control. An intrusion detection system and CCTV are also used. Data are being collected to review operations and look for needed improvements.

Oresund Tunnel Between Denmark and Sweden

The control room has two operators around the clock: one responsible for the technical installation and road operations and the other responsible for toll station operations and customer assistance. The operators are cross trained. A backup control room is located at the Danish police station in Copenhagen and is being moved to a new location.

Communication is by frequency modulation (FM) radio in the tunnel and trains. The operations center can interrupt the radio channel for emergency announcements. Rescue services have their own radio communication that is common to both Swedish and Danish forces.

For traffic monitoring and control, the Oresund tunnels have fixed cameras every 60 m (200 ft) and portal cameras every 500 m (1,640 ft), for a total of 250 cameras in the open. Barriers are used to close the link, with dynamic signs that give directions for speed, lane use, and messages. No cameras are in the rail side and the shipping lanes are not monitored. Over-height vehicles hit the tunnel about twice a year. Oresundsbro Konsortiet has an agreement with the local coast guard for inspecting areas away from the bridge/tunnel.

Vehicles are monitored with cameras. Images are sent to a server and processed, and an incident can alarm the operator. The camera will automatically switch to the zone in the tunnel where the incident is occurring. The action must be something that moves and then stops; the camera will not find small objects such as bags.

A Belgian company makes the hardware and software that connects to the cameras to identify an incident. The system can produce false alarms near the tunnel entrance. Noise, mast pole vibration, or even an insect on a camera lens can trigger a false alarm. These problems require the operator to concur that the alarm is because of a real incident before action occurs to mitigate. This system has been in place for 5 years and is being continually improved to get better performance, but it is considered unlikely that it will soon be practical to alarm for automatic action. The tunnels have about 10 stopped vehicles per month and these are considered a source for a potential crash since the tunnel has no emergency lanes. The goal is to remove such vehicles within 20 to 30 minutes. So far, no crashes have resulted from stopped cars.

Previously the evacuation concept was to evacuate passengers from an incident train to the opposite railway tube. The new concept to be implemented in 2006 is to evacuate passengers to the motorway tube.

Jet fans in the tunnel system are designed to operate in lines of fans called line control. When a fire occurs, the control room activates more fans. In December 2004, this was changed to group control of fans. Now if a fire occurs, a group of fans on the output of the affected tunnel are turned on to make an over-pressure to keep the smoke in the original tube and the entrance fans in the unaffected tunnel are turned on. This also eliminates the fan noise to improve emergency crew operations.

Escape doors in the tunnel are spaced at 88 m (290 ft). These doors are left unlocked between highways and railway, although there is no handle on the highway side; originally electronic locks were installed but these have been removed. Fire hydrants are also spaced every 88 m (290 ft). On the wall opposite the door is an emergency panel with a fire extinguisher, telephone, and alarm. Users can open the door by pressing a button; when the door is opened, an alarm goes off in the control center directing CCTV to the door. The automatic fire alarm system provides gas extinguishing, water spray, and foam. The tunnel has a fireproof layer on the ceiling and 1 m (3 ft) down the walls. To date, the tunnel has had some smoke from damaged cars and tires but no large fire incident.

Movable barriers are 300 m from the portals and are used for changing traffic direction if one of the tubes is closed for cleaning or an emergency.

Oresundsbro Konsortiet works with three levels in rescue operations. Level 1 is the lowest and has the least needs: Danish assistance only for Denmark and Swedish assistance only for Sweden (e.g., for a small single-car crash). Level 2 is a two-way response; emergency services are needed at the incident as fast as possible. Level 3 is the highest level (e.g., train crash fire or two-way turnout). Several hundred scenarios have been classified into 11 broad scenarios. A car fire on the artificial island would be Level 1, and smoke in the tunnel would be Level 3. No Level 1 is specified for trains.

Language and cultural differences exist between Sweden and Denmark. To make an alarm based on a telephone call and alarm 12 stations is significant. Therefore, Oresundbro Konsortiet bought a computer system in Sweden and loaded 11 incident scenarios. The operator does not determine Level 1, 2, or 3; instead, the operator answers four questions on a dropdown menu and pushes a button. The computer will sequence the equipment, depending on the given scenario. It takes less than 3 minutes for the alarm to be sent out in both languages, saving time and confusion between languages and cultures.

Special rescue equipment needs were assessed. It was determined that a need exists for water systems, infrared cameras for smoke, a fire brigade using motor bikes and water mist tanks to easily get to the fire, and medical assistance.

The 2 years of planning resulted in four books. One book has drawings of the entire link shown from the perspective of rescue workers. The second book has the emergency plan with details on the 11 scenarios, as well as a description of how to organize response to an incident. The third book is an education catalog. The fourth book is for equipment and evaluation of all full-scale exercises. Their first priority is to save lives.

Citytunnel Railway in Sweden

The Citytunnel will have the first underground railway stations in Sweden, and for these stations emergency evacuation plans and regulations will be developed. Because the system will also use Danish trains, Danish regulations were considered along with Swedish regulations. The standards now are to evacuate trains at the stations or outside the tunnel, if possible. Evacuation must be completed before critical conditions are met. Critical conditions are defined as smoke, radiation, and temperature not to exceed a certain limit and visibility to 10 m (33 ft). If the train must stop in the tunnel, the evacuation is to be completed before lethal conditions are met. "Lethal" is defined as conditions not conducive to supporting life. Smoke and fire calculations are compared to the evacuation simulations for the design basis. The intent is for 800 passengers to be able to evacuate to the other track tunnel via the 1.2-m (3.9-ft) wide walkways before lethal conditions occur. A new European standard for high-speed trains is for the train to be able to travel 15 minutes at 80 km/h (50 mi/h) with a fire on board.

Discussions on safety regulations include what circumstances required special traffic restrictions, such as evacuation capacity is limited, control center is down, electrical current is disrupted, or communication systems have failed. Communications are by radio and mobile, regular, and emergency phone systems.

Terrorism and intentional acts of destruction are just now being discussed.

CETU in France

CETU described the approaches used for evacuation of people in French tunnels. The approaches varied with the type of tunnel construction, including cut-and-cover construction, in which stairs could be used to provide cost-effective evacuation and emergency access; two-tube tunnels, in which the adjacent tube provides a means for evacuation through connecting cross passages; tunnels with separate evacuation tube/gallery; and single-tube tunnels. The single-tube tunnel is a much more difficult situation and is generally dictated by the type of tunnel ventilation design. For transverse ventilation, refuge/shelter rooms are built and the fresh air gallery can be used by emergency services for evacuation of users from the shelters; for longitudinal ventilation, no good solution exists. Long single-tube tunnels with longitudinal ventilation are not allowed in France. CETU noted the importance in all instances of adequate signage and other means, such as visual and audio notification, to direct people to the nearest evacuation route. The French directive is to provide emergency exits at 200-m (656-ft) intervals in urban tunnels and 400-m (1,312-ft) intervals in other tunnels.

Video surveillance, used in all manned tunnels, monitors tunnel activity and automatically detects stopped vehicles. Tunnel operations also monitor sensors for nitric oxide (NO), carbon monoxide (CO), airflow, and opacity. Regulations on safety in tunnels provide thresholds for safe operation.

Communication problems between tunnel operators and emergency response agencies include the loss of radio and phone communications in the tunnel because of fire damage to communication facilities (radiating cable) or the effects of ionization of the air. Also, a common problem encountered was the use of different radio systems by emergency response agencies. Harmonization of frequencies or other means need to be provided to ensure communication among all agencies. Also, means must be provided, such as emergency phones, for informing drivers of emergency information, particularly in the event of a fire incident in a tunnel.

CETU has developed a process for safety procedures and documentation that provides a common understanding of the analysis and evaluation required, continuing feedback from tunnel operators, and an upgrade program for existing tunnels. This is provided as a *Guide to Road Tunnel Safety Documentation.*

CETU officials indicated that they do not consider terrorist threats a significant issue. They look at this in the design phase to see what can be done to detect and deter such incidents. Their primary interest is to detect or, if not possible, to respond quickly, using formal emergency response plans. They developed the following procedures to respond to explosive threats, although it was not clear whether all tunnel operators have adopted them:

- Call-in procedure for a bomb threat: The operator takes and records information, closes the tunnel to traffic, and calls the police to check out the threat.
- Suspicious object in tunnel: Traffic should be stopped at least 1,200 m (0.75 mi) from the object while the police respond.
- Car stopped in tunnel: Stop all traffic and direct drivers and passengers to enter the emergency shelters.

CETU has not included provisions or requirements related to radiological, chemical, or biological incidents, apart from those related to dangerous goods incidents. Further studies are required in this area.

STUVA in Germany

The German practice is to provide security or refuge stations at 300-m (984-ft) spacing.

STUVA noted that before the terrorist incidents in New York, Madrid, and London, little attention was given to explosive incidents but that consideration is now given for mass transit applications. There is some application for flood control measures in mass transit tunnels in England and Germany but, because of the expense, not for long-distance train tunnels.

Mont Blanc Tunnel Between France and Italy

The tunnel has one control room in each portal. Only one control room operates at any one time, and the other is on standby. If a problem occurs at the control room, the control can be instantly changed to the other control room. Two operators are in the active control room and one operator is in the other control room.

Generally, power is supplied to half the system from each end. In the event of a power failure from one end, power can be provided from the other end. The tunnel has an uninterrupted power supply system with no backup generators. Sensors detect the levels of CO, NO, and opacity, with 20 sensors for each.

A space between vehicles of 150 m (490 ft) is mandatory; violators are fined. On a typical day, 1,600 trucks cross the tunnel. Traffic regulations exclude trucks with dangerous goods and trucks made before 1993 because of pollution controls. Checks are made at regulation areas for these exclusions and also to check the truck size. A ticket shows that the size and pollution level are acceptable to cross the tunnel. Truck controls are at both portals. A laser system determines the truck size. The trucks also pass through a thermal detector to identify any unusual heat (see figure 17). If a problem is detected, the truck will not be allowed to enter the tunnel, and it must be towed. Truck volume is regulated by law, with not more than 240 trucks per hour allowed to cross the tunnel. When the tunnel must be evacuated, the toll operators are in charge of taking small minivans into the tunnels to pick up individuals.

The velocity of air inside the tunnel can be controlled and a zone of zero velocity can be set using the automatic system. A yellow vertical line on the screen in the control room shows air speed equal to zero (see figure 18). This point can be placed anywhere in the tunnel in 2.5 to 3 minutes to change the location of zero air

Figure 17. *Truck thermal detector at the Mont Blanc Tunnel.*

flow, safely extract smoke, and make emergency evacuation and rescue easier.

Along the tunnel length are 37 refuge rooms at 300-m spacing, all on one side with a pullout area across from each refuge room (see figure 19). The refuge rooms are equipped with a video phone and written instructions in three languages that inform individuals that they are safe, that fresh air is being provided, and that the operators know their location (see figure 20 on page 28). Signs direct individuals to remain inside the refuge room and not return to the tunnel. Refuge rooms can provide 2-hour protection; escape from the refuge rooms is possible through the fresh air plenum. When there is a fire, overpressure will be initiated in the refuge rooms so that smoke cannot enter. The air exchange in the refuge rooms is 20 m^3/h (540 ft^3/h). The difference in air pressure between the refuge room and the tunnel is 80 pascals. Smoke is extracted by a longitudinal duct under the roadway.

Eighteen variable message signs are located at 600-m (1,970-ft) intervals to direct people to refuge rooms; the messages are in French, Italian, and English. About 20 barriers are also equipped with small variable message signs. FM radio override is available in the tunnel for the 12 radio stations, 6 French and 6 Italian.

A unique air duct below the roadway is reserved for extraction. Extraction ducts are positioned along the curb line. During a fire, dampers are activated. Four fans are needed and an additional two fans are for backup. Temperature is measured along the entire length of the tunnel with fiber-optic sensors; a red horizontal curve on a screen in the control room shows the temperature curve of the air inside the tunnel in real time. The middle of the tunnel is always at 25 °C. The system will detect a rapid increase in temperature and automatically activate the emergency systems. Jet fans are single speed and reversible. Wet standpipes are used, and a system is in place to keep the pipes warm. There are 200 cameras in the tunnel.

Security procedures now include three blast scenarios:

- An operator, secretary, or other personnel gets a bomb threat: The individual receiving the threat completes a form to try to identify the caller. The tunnel is closed. The police are called and they initiate their procedures.
- A suspect or suspicious activity is seen: Traffic is stopped 1,200 m (0.75 mi) short in both directions to empty the tunnel on either side of the suspect or suspicious activity. A small bus is sent to pick up motorists from the refuge rooms.
- A car is stopped in the tunnel: If an explosion is possible, traffic is stopped and motorists are sent into the passageways from the refuge areas not in the blocked area. People are told via variable message signs and radio to access the refuge areas. Automatic incident detection video can help operators make the proper judgment.

Currently the scenarios look only at explosives; no WMD procedures have been developed.

Special high-tech trucks protect the Mont Blanc Tunnel in the event of a fire (see figure 21 on page 29). These trucks have a steering configuration that allows lateral movement and an extremely small turning radius. Foam can be released from the bottom of the truck, and a hose positioned on its roof can propel water a significant distance. A video camera is mounted on the front of the truck, and the truck is loaded with a variety of safety and firefighting equipment. These trucks, unique to the Mont Blanc tunnel, cost about €450,000 (US$540,000) each.

Figure 18. *"One-button" response for incident management in the Mont Blanc Tunnel.*

Figure 19. *Emergency pullout area across from refuge room in the Mont Blanc Tunnel.*

Gotthard Tunnel in Switzerland

As a result of growing traffic, the sense was that risk was growing and actions were required to address fire issues in the Gotthard Tunnel. Incident management also is a major factor with driver behavior such as U-turns. Firefighting equipment includes trucks with a turntable that can be lowered to reverse engine direction in the tunnel. Smaller equipment is also used for tight situations. Traffic control in Switzerland is handled strictly by Swiss police. Exercises are extremely important and should be conducted in the tunnel.

The Gotthard Tunnel incident plan covers 18 scenarios ranging from minor crashes to leakage of hazardous materials, but none that deal with terror attacks.

Crashes decreased significantly when limits were put on the volume of traffic that can be in the tunnel at any one time. This was done by instituting criteria for distance between vehicles. A minimum spacing of 150 m (490 ft) between trucks and 50 m (160 ft) between cars was effective in reducing traffic crashes from 35 to about 10 per year. Sensors are used to assess the composition of the incoming traffic to control the volume.

Loetschberg Tunnel in Switzerland

Cross passages 40 m (130 ft) long are constructed at 333-m (1,090-ft) intervals. The cross tunnels are separated from the rail tunnels by sliding doors rated for 1,000 °C (1,820 °F) for 90 minutes. If an emergency incident in a rail tunnel makes it necessary for people to escape, they make their way to these cross passages. A metal handrail attached to the tunnel wall on the cross passage side is installed to help people find their way to the cross passage. In general, the rail tunnels are not lighted but they do have emergency lights mounted at eye level and spaced at 12.5 m (41 ft) to help guide evacuees.

Evacuees will be transported out of the tunnel by an evacuation train, which is available on standby for this purpose, or buses, depending on where the evacuees have taken refuge. Until the dual tubes are fully constructed, buses will be used in the incomplete (carcass) tube where available. In another section, the exploratory tunnel that was bored to determine geologic conditions before the main construction began will be used for evacuation.

Figure 20. *Mont Blanc refuge room. Top: inside refuge room. Bottom: instructions posted on wall.*

Plabutsch Tunnel in Austria

Two redundant operations centers are provided for data transfer and operations control. Tunnel operators are required to be competent electricians and go through a training program of 1 to 2 weeks in the control room and 1 to 2 weeks in the tunnel as part of a maintenance crew before they can work a shift on their own. To prevent data overload for the system and operators, data are sent by exception for changes in baseline condition only; this also speeds up alerts since it reduces processing time.

Firefighting water supplies are located at 106-m (348-ft) intervals throughout the tunnel. Fire extinguishers are located at each water supply box along with a hydrant and in each emergency call box, located every 212 m (696 ft). Hoses with tube length of 100 m (328 ft) are located in all emergency parking niches.

Fire detection is based mainly on a linear heat detector. Smoke detection is automatic via a proprietary system. Automatic detection with CCTV and automatic gas detection are obtained with alarms at the control center that, if confirmed, result in manual activation of fire protocols. Information from an emergency call box, voice, or button, if confirmed in the control center, results in manual activation of the fire alarm. Automatic notification when a fire extinguisher is taken from its holding device, if confirmed in the control center, results in manual activation of the fire alarm.

Two emergency escape exits are located at third points. Cross tunnels are provided every 424 m (1,390 ft) for people and at 1.6 km (1.0 mi) for vehicles. It was again stressed that self-rescue and human behavior in the first 10 minutes of the incident are critical for survival.

Maintenance and Safety Inspection

Rambøll Risk-Management Approach to Safety Inspection and Maintenance

Rambøll uses a risk-based approach to safety inspection and maintenance. The trend is to use ongoing monitoring of structural condition. Rambøll staff track the data from their principal (comprehensive) periodic inspections. They accurately record what was done (type of equipment used, etc.) in the inspection so they can evaluate the results properly. With this approach, started in the 1990s, they are accumulating records of the progression of structural deterioration. They are using the data to develop deterioration modeling to determine the existing safety level and ensure that a minimum required level is maintained. The purpose is to optimize the use of available funds, extend the service life of the facility, and minimize traffic disruption.

Nondestructive testing for corrosion is an important method for obtaining data to use for deterioration modeling. Corrosion sensors in combination with online monitoring systems are being used to enable better assessments of condition and also provide the ability to monitor areas of the structure that are difficult or impossible to access.

Oresund Tunnel Maintenance Plan

The police authority has responsibility for road traffic and restrictions for maintenance. Oresundsbro Konsortiet made an agreement with the police authority on how to restrict traffic for maintenance that allows the organization to apply its own traffic restrictions.

The primary maintenance plan is the Link Works Programme (LWP). The LWP is updated every week. The traffic department maintains the plan and keeps track of the number of people onsite. Access is allowed only with a job number from LWP. A crew member notifies traffic control when the crew leaves the site. Traffic costs are related to job numbers. All money related to work can be related to this job number.

Oresundsbro Konsortiet is now putting all maintenance planning into a central database called Maximo developed by Maintec, a Danish company. The database has 5,000 objects, but not all objects from all contractors are identified. Inputting costs is not required because of the concern that other contractors might see the numbers.

One-lane closure is used for maintenance work. Skylifts are not allowed in the tunnels. Only scissor lifts are allowed. Twice a year, the tunnel is closed and 150 people work at night. Inside and outside, variable message signs are used for lane closures.

The motorway tunnels are washed every 3 months, one side at a time. The process takes 2 weeks. Sensors in the pavement monitor the temperature, which is typically 8 to 10 °C (46 to 50 °F). Weather stations with pavement sensors are at portals.

CETU Tunnel Maintenance Approach

Maintenance is performed with the help of automated data management systems that record and save specified information for status and analytical purposes and that also provide self-diagnostic functions to identify and locate faulted devices. The goal is to establish a preventive maintenance program using information on mean time to failure (MTTF) for systems, subsystems, and components. CETU indicated that this was difficult to apply because of the vast number of different devices and suppliers as well as the general lack of MTTF information for application in road tunnels.

Project Delivery

New E39 Highway in Norway

A public-private partnership made the new E39 highway near Tronheim in Norway possible. The route has six rock tunnels and one cut-and-cover tunnel. Video surveillance is used in the two longest tunnels. Speed sensors are installed in the tunnels, and one operations center enables operators to monitor all of the tunnels

Figure 21. *High-tech firefighting truck for Mont Blanc Tunnel.*

and control tunnel access from one location. The tunnel has had zero lost time because of crashes.

This public-private partnership enabled the project to be constructed in 26 months. It was estimated that if the project had been done under the normal method with the Norwegian Public Roads Administration proposing, designing, and contracting the construction, it would have taken perhaps 5 years longer. The partnership—including the Public Roads Administration; Orkdalsvegen AS, the financier operator; and Skanska, the constructor—uses the unique capabilities of each to carry the elements of risk in those parts of the work where each has the greatest ability to limit the risk. Sharing risk allows for greater innovation and flexibility to deal with problems as they arise.

Orkdalsvegen will operate the facility for 25 years. The Public Roads Administration will collect toll revenues and make large payments to Orkdalsvegen for the first 3 years and lesser ones for the remaining 22 years. The payment plan allows Skanska to be paid for the construction, Orkdalsvegen to receive a positive return on its investment, and the Public Roads Administration to meet the public's demand for an improved highway system. The arrangement also encourages quality in workmanship; Orkdalsvegen is responsible for maintenance for 25 years, so it benefits greatly from sound construction and low life-cycle costs.

Citytunnel Railway in Sweden

The Citytunnel E201 Tunnels and Triangeln Station in Malmo are owned by the National Rail Administration and operated by private companies. Different packets of work are split up among different contractors. It is a SEK2.4 billion (US$300 million) design-build contract with schematic design by the client.

For the construction procurement, the owner will purchase two tunnel boring machines that the civil works contractor will use to simultaneously drive two tunnel bores. One civil works contractor is responsible for all of the civil works and coordination with the other train operation contractors.

The civil works contract will be a design-build contract with a shared-risk approach to the geotechnical conditions, which are supplied by the owner. A negotiation process for additional payment will take place if conditions change significantly. No independent engineering checks are required, although an independent checker reviews drawings and methods for temporary works that could result in damage. The contractor will prepare his own construction schedule and is responsible for quality control. The owner audits the paperwork but does almost no quality assurance. Payment is made as the contractor reaches milestones, with very few measurements taken. The owner puts its trust in the suppliers.

Partnering is limited under legislation for public procurement. However, the owner has participation in procurement of key equipment, a joint seminar for risk identification, input on temporary works designed to minimize risks, and regular joint construction meetings on critical activities such as water drawdown. The primary construction risks are expected to be groundwater, settlement, and delays due to environmental concerns about chemicals used on the project. The risk-management principles are in accordance with an EU and United Kingdom document entitled *A Code of Practice for Risk Management of Tunnel Works,* as done for the Oresund Link.

Recommendations and Implementation Strategy

Team members identified a number of underground transportation system initiatives or practices that varied from those in the Unites States in some respect. The team recommended that nine of these initiatives or practices be further considered for possible implementation in the United States.

Little was discovered related to the threat from terrorism to underground structures, perhaps because of the confidential nature of this information or the lack of perceived need for such measures. The scan team learned that the Europeans consider response and safety measures already in place for crashes and other incidents to also be applicable for many terrorist actions.

The nine initiatives and practices the scan team identified are described below. Included are the team's assessment of the benefits of each initiative or practice and the planned implementation strategy.

1 Develop Universal, Consistent, and More Effective Visual, Audible, and Tactile Signs for Escape Routes

The scan team noted that the signs Europeans use to indicate emergency escape routes are consistent and uniform from country to country. Emergency escape routes are indicated by a sign showing a white-colored running figure on a green background. Other signs that indicate the direction (and in tunnels, the distance in meters) to the nearest emergency exits are similarly indicated by a white figure on a green background, as used in European buildings and airports. See figure 13 for examples. All SOS stations in the tunnels were identified by the color orange. This widespread uniformity promotes understanding by all people, and helps assure that in the event of an emergency, any confusion related to the location of the emergency exit will be minimized. In addition, the team learned that the use of sound that emanates from the sign, such as a sound alternating with a simple verbal message (e.g., "Exit Here"), when combined with visual (and, where possible, tactile) cues, makes the sign much more effective.

The U.S tunnel engineering community relies on NFPA 130, *Standard for Fixed Guideway Transit and Passenger Rail Systems, and NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways,* for fire protection and fire life safety design standards. These standards should be reviewed and revised as necessary to incorporate the most current technology and results of recent human response studies on identifying and designing escape portals, escape routes, and cross passages.

Implementing this practice will provide the benefits of reducing the time it takes for motorists to get to a safe location during the initial stages of a tunnel emergency and improving the efficiency of the evacuation process.

The implementation strategy includes promoting the use of easy-to-recognize multisensory signs that are uniform and consistent, and providing input and assistance for inclusion of these signs in tunnel design manuals and standards.

2 Develop AASHTO Guidelines for Existing and New Tunnels

Single-source guidelines for planning, designing, constructing, maintaining, and inspecting roads and bridges have been in place for many years. NFPA has developed standards for safety in highway tunnels and passenger rail tunnels. APTA has general safety standards and guidelines for passenger rail operations and maintenance, with incorporation of some of the NFPA guidelines by reference. However, AASHTO does not have standards or guidelines specifically for highway or passenger and freight rail tunnels. Recently, the AASHTO Subcommittee on Bridges and Structures created a new committee, the Technical Committee on Tunnels (T–20), to help address this problem. T–20 should take the lead in developing AASHTO standards and guidelines for existing and new tunnels, working with NFPA, APTA, FHWA, and the appropriate TRB committees on standards and guidelines for highway and passenger and freight rail tunnels. T–20 should consider tunnel safety measures such as the Mont Blanc Tunnel emergency pullout area and variable message sign showing maximum speed limit and required vehicle spacing, as shown in figure 19, as well as refuge room requirements, as shown in figure 20.

Implementing this initiative will provide the benefits of creating a single-source AASHTO reference for use by tunnel engineers and operators. This reference will facilitate the use of consistent criteria in U.S. tunnels.

The implementation strategy includes review of the ongoing FHWA Tunnel Design Manual project, and coordination with AASHTO, FHWA, NFPA, APTA, and TRB on standards and guidelines for highway tunnels and passenger and freight rail tunnels.

3 Conduct Research and Develop Guidelines on Tunnel Emergency Management that Includes Human Factors

Tunnel design solutions may not anticipate human behavior, and consistently predicting the way people will behave in an incident is not easy. During emergency situations, human behavior is even harder to predict as the stress of the situation replaces intellect with curiosity, fear, or even panic. During a tunnel emergency, people often must be their own first rescuers and must react correctly within a few minutes to survive. Tunnel emergency management scenarios and procedures must take human behavior into account to be fully effective in saving lives. The European experience in human factor design provides a good basis for the United States to discover and include more effective measures for tunnel planning, design, and emergency response.

Implementing this initiative will provide improved emergency response plans to enable response teams to better handle situations, thereby mitigating the consequences of an incident. Its implementation will also improve the ability of planners and designers to address security and safety issues in tunnel design, and improve the ability of tunnel owner-agencies to provide training and guidance to the public on how to respond when an incident occurs in a tunnel.

The implementation strategy includes working through the AASHTO HSCOBS Technical Committee for Tunnels (T–20) to fund and develop guidance for tunnel emergency management. Part of this effort will be to reach out to academia to perform studies on human response in tunnel incidents. The work done by the Europeans (PIARC Working Group 3) in this area can be used to promote the importance of human response studies in the United States.

4 Develop Education for Motorist Response to Tunnel Incidents

During an emergency situation, most people do not immediately know what to do to save themselves and others. Motorists are their own first rescuers, and European studies indicate that self-rescue may be the best first response for a tunnel incident. For this to be an effective strategy, it is important to educate the public about the importance of reacting quickly and correctly to a tunnel incident, such as a fire.

Road crashes are the consequence of one or more faults in a complex system involving drivers, vehicles, the road, and its surroundings. Nevertheless, the major factor in road crashes is human error, so efforts to increase the level of road safety must be aimed primarily at preventing these human errors. The main benefit of this initiative is to avoid loss of lives by making motorists aware of safety features in U.S. tunnels and how to react properly in case of an incident in a tunnel. Also, proper education will help motorists avoid human errors that can lead to incidents.

The implementation strategy includes working with AASHTO, NFPA, the American Automobile Association (AAA), and TRB on outreach, including preparing brochures, articles, and presentations for conferences, schools, and other venues. Other efforts under consideration are development of television and radio public announcements, a video for professional drivers, and a pilot tunnel safety program with the States.

5 Evaluate Effectiveness of Automatic Incident Detection Systems and Intelligent Video for Tunnels

The scan team learned of sophisticated software that, using a computer system interfacing with ordinary video surveillance cameras, automatically detects, tracks, and records incidents. As it does so, it signals the operator to observe the event in question and take the appropriate action. This concept can also be applied to detect other activities and incidents in areas besides tunnels, from terrorist activities to crashes, vandalism and other crimes, fires, and vehicle breakdowns.

Widespread public use of CCTV is not as readily accepted in the United States as in other countries because of privacy concerns. However, people are entitled to security, and the implementation of this technology in the United States is expected to provide the benefits of defining the usefulness of the technology and, if practical, encouraging its adoption by tunnel operators and engineers in their tunnel operations. The goal is to decrease the time it takes to detect an incident and respond to it.

The implementation strategy includes outreach to describe the technological capabilities now available and to explain the safety benefits and possibilities of using this technology.

6 Develop Tunnel Facility Design Criteria to Promote Optimal Driver Performance and Response to Incidents

Europeans found that innovative tunnel design that includes improved geometry or more pleasing visual appearance will enhance driver safety, performance, and traffic operation. For example, the full-size model of one section of the twin roadway tube for the A–86 motorway in Paris, shown in figure 9, demonstrates the effectiveness of good lighting and painting to improve motorist safety. It is a particularly important consideration for a tunnel roadway section designed with limited headroom. Tunnel designers should evaluate the materials and design details used to reduce risks to ensure that they do not pose other unacceptable hazards. For example, paint used to enhance the visual experience should not produce toxic fumes or accelerate fire.

Implementing this practice will provide tunnel designers, owners, and operators with guidelines for tunnels that will ultimately result in improved tunnel safety.

The implementation strategy includes conducting an internal U.S. tunnel scan, and working with AASHTO T–20, FHWA, NFPA, and TRB to develop standards and guidelines for road tunnel emergency response management.

7 Investigate One-Button Systems to Initiate Emergency Response and Automated Sensor Systems to Determine Response

The European scan revealed that one of the most important considerations in responding to an incident is to take action immediately. For this to be effective, the operator must initiate several actions simultaneously. An example of how this immediate action is accomplished is the “press one button” solution that initiates several critical actions without giving the operator the chance to omit an important step or perform an action out of order. On the Mont Blanc Tunnel operations center control panel shown in figure 18, operators can initiate several actions by moving a yellow line over the area where a fire incident is indicated on a computer screen. This “one-button” action reduces the need for time-consuming emergency decisions about ventilation control and operational procedures.

The Europeans observed that tunnel operations personnel have difficulty keeping up with events like tunnel fires, and they believe that an automatic system using devices like opacity sensors can be helpful in determining the correct response. A closed-loop data collection and analysis system that takes atmospheric conditions, tunnel air speed, and smoke density into account may best control fans and vents.

Implementing this technology will provide the benefits of reducing the time required to start tunnel ventilation and traffic control systems and reducing the need for an operator to make subjective decisions on emergency operations.

The implementation strategy includes reaching out to planners of new or upcoming major tunnel projects, describing through presentations and training efforts the technological capabilities now available, and promoting the potential safety benefits from using this technology.

8 Use Risk-Management Approach to Tunnel Safety Inspection and Maintenance

The scan team learned that some organizations use a risk-based schedule for safety inspection and maintenance. Through knowledge of the systems and the structure gained from intelligent monitoring and analysis of the collected data, the owner can use a risk-based approach to schedule the time and frequency of inspections and establish priorities. It makes more sense to inspect less critical or more durable portions of the system on a less frequent basis, and concentrate inspection efforts on the more critical or more fragile components. A risk-based assessment of the condition of facilities also can be used to make optimal decisions on the scope and timing of facility maintenance or rehabilitation. This method offers a statistical process to manage the tunnel assets.

Implementing this practice will help tunnel operators establish risk-based maintenance and safety inspection procedures to help maximize their resources without compromising safety to the public.

The implementation strategy includes promoting the use of tunnel management systems, and working with AASHTO and FHWA to establish guidelines for conducting and reporting tunnel safety inspections on a routine basis.

9 Implement Light-Emitting Diode Lighting for Safe Vehicle Distance and Edge Delineation in Tunnels

The scan team noted that in several European tunnels, LED lights were installed along the edge of the tunnel at regular intervals of about 10 to 20 m (33 to 66 ft) to clearly identify the edge of the roadway (see figure 14). These lights were either white or a highly visible yellow color. In some tunnels, blue lights were spaced among these edge-delineation lights at 150-m (490-ft) intervals. See figure 15 for examples. Motorists are instructed through formal (for truck and bus drivers) and informal driver education to keep a safe distance between them and the vehicle in front, and that distance is indicated by the spacing of the blue lights. This visual cue is more reliable than asking motorists to establish distance between vehicles using speed-based guidelines (i.e., maintain one car length spacing for every 16 km/h (10 mi/h) of speed). The LED markers are also less susceptible to loss of visibility because of road grime and smoke during a tunnel fire.

Implementing this technology will provide the benefit of increasing driver awareness of the roadway/tunnel limits, thus increasing safety. While driving in tunnels, motorists typically and unconsciously move away from the edge of the tunnel and crowd the centerline. In bidirectional tunnels, this means opposing vehicles pass dangerously close to one another. Also, following too closely is an endemic problem on our Nation's highways, but the risks increase significantly when vehicles follow too closely in tunnels. Using blue LED lights at a given spacing will make it easier for drivers to gauge the distance to the vehicle in front and help them maintain safe spacing. Future guidelines should include recommending to designers that white or yellow LED lights be established as roadway edge delineation and blue LED lights be established at the recommended following distance, which will vary with the tunnel design, traffic count, and speed limit.

The implementation strategy includes working with AASHTO and FHWA on outreach to tunnel owners to advocate installing such devices and to drivers to educate them on what the LED lights mean and how to use them to gauge the lateral location of a vehicle in its lane and the distance between vehicles. This training could be incorporated into driver education.

Amplifying Questions

TOPIC 1 Planning approaches, standards, manpower roles and responsibilities, and communication techniques to deter, detect, defend, respond to, and recover from both natural and manmade disasters and other incidents

1. Does your country have a national standard for tunnel design?
2. What variation in types of tunnels exists with respect to cross-sectional dimensions, presence of lining, type of lining, and level of mechanical systems such as ventilation, fire suppression, and tunnel monitoring systems?
3. How does adjacent infrastructure, land use, or topography influence planning and design?
4. What guidance and standards are provided to planners and designers to address vulnerabilities to natural and manmade disasters for new and retrofitted tunnels? Is blast design included?
5. Are you moving toward performance-based design rather than the prescriptive approach and, if so, how are you addressing issues such as life safety, acceptable risk, and fire size?
6. Are risk assessments addressed programmatically for highway and rail/subway tunnels and, if so, how are the programs developed and funded? Do you use an all-hazards approach, and how do you handle specific risks that cannot be mitigated?
7. What traffic management and safety innovations are deployed or planned to minimize or eliminate problems such as congestion at highway tunnel toll collection locations?
8. What are your protocols for tunnel operation center management? Our interest includes the role of law enforcement and laws or regulations that promote effective response and recovery. Also of interest are human factors that influence your procedures.
9. How are communication procedures, equipment, and jurisdictional issues integrated among law enforcement, emergency responders, and operation control center personnel? Which agency has the role of incident commander?
10. Are there laws or regulations in place or under consideration for motorist identification, cargo tracking and control, criminal investigation, or other purposes aimed to deter terrorist actions?
11. Do you actively screen or otherwise monitor truck cargoes entering your tunnels and, if so, how do you screen them without disrupting the flow of traffic? What dangerous cargo is acceptable, and how is this enforced?
12. What protocols do you use to vary responses to hazards depending on different types of indicators (e.g., weather alerts or changes to threat levels)?
13. What best practices can you share in the areas of prevention, mitigation, response, and recovery from manmade and natural disasters?
14. How are staffing and equipment needs established for normal work and for emergency work?
15. What processes and standards are employed to conduct background checks on employees and vendors and ensure confidentiality of information pertaining to assets?
16. What types of exercises and other training are provided to staff and first responders to ensure proficiency in response to an incident, and how is this training evaluated?
17. What notification are motorists given as they approach a tunnel, and what safety training are they given on driving through a tunnel?
18. How does your agency interact with the media?

TOPIC 2 Available state-of-the-art products and equipment used to deter, detect, defend, respond to, and recover from tunnel incidents

1. What communication systems are used (e.g., to communicate with rescue personnel inside a tunnel)?
2. Are you using human behavior recognition technology in conjunction with video surveillance and intrusion detection technology and, if so, where and how are you using it?
3. Have you developed recovery strategies for possible tunnel wall breach (as from an explosive), particularly for those tunnels subject to flooding? Have you considered any measures to mitigate such a breach or lessen its impact?
4. What innovations are you using for emergency egress and for effectiveness to deter, detect, defend, deny, respond to, and recover from terrorist actions or other incidents (e.g., robotic or other automated technologies, lighting, cameras, sensors, structural configuration, ventilation control, communication technology, weapons-of-mass-destruction (WMD) detection technology, and fire suppression technology for both new and retrofitted tunnels)?
5. What vehicle identification technologies and cargo tracking technologies are used in your facilities?
6. What equipment and materials are pre-positioned for response and recovery to an incident (e.g., for quick removal of a disabled vehicle), and what is considered acceptable response time?
7. What technology is used to control access to or create buffer zones for critical details and areas?
8. How are access control and surveillance handled under normal operations? Are your tunnels monitored around the clock and, if not, what equipment and methods do you use to secure the facilities during off-hours?

9. What types of sensors are in use and for what types of hazards? Has an evaluation of sensor effectiveness been done (e.g., sacrificial heat sensors in new construction, water intrusion/level sensors, fire sensors, explosion sensors, WMD sensors)?
10. What types of technology are in place to ensure proper command and control and interoperability of equipment for first responders?
11. How do you detect over-height vehicles before they enter tunnels, and do you use cameras to automatically fine vehicles that have damaged your facilities?
12. What new materials are being used to protect your tunnels (e.g., concrete with plastic fibers), and how have these new materials performed?
13. What has been the performance of refuge rooms?
14. What technology is used to detect tunnel fires (e.g., linear heat detectors, carbon monoxide monitors, traffic camera feeds, fire alarm call boxes, or some combination of these devices)?
15. How are jet fans protected from fire and other attacks?
16. Have you identified gaps in research for tunnel safety, security, or other areas? Can you suggest strategies for cooperative efforts in research to solve common problems and promote safety?

TOPIC 3 Specialized technologies and standards used in monitoring or inspecting structural elements and operating equipment to ensure optimal performance and to minimize downtime during their maintenance or rehabilitation

1. Do you have a maintenance management system to manage all of the electrical/mechanical systems required to operate your tunnels? If so, is it capable of assigning preventive maintenance tasks to your maintenance forces, and does it track actual performance against the manufacturer's recommended maintenance schedule?
2. What inspection and rating programs do you have in place to detect potential performance issues and to help plan maintenance and preservation activities?
3. What are your protocols for periodic inspections for security and other hazards (e.g., how often and by whom are your mechanical systems inspected)?
4. How quickly are you able to detect and clear routine traffic crashes inside your tunnels? Do you have emergency response platforms or stations strategically located along the alignment? If so, are the tow truck operators your own employees, or do you contract out for these services?
5. What equipment is provided in each tunnel for inspection, maintenance, and emergency response? How is this equipment maintained and tested?
6. How often are tunnels inspected for structural condition, who does the inspection, and what equipment is used (e.g., lift bucket for access to the ceiling)?
7. What methods are used to inspect the structural integrity of the concrete and the steel, both routinely and after a fire, and what materials are used to repair concrete after a fire?
8. What innovations do you use to prolong service life and reduce operational costs, particularly those that may provide multiple benefits related to safety and security?
9. If you had your wish to start a new tunnel project, what key elements would you incorporate in its design and construction to aid you in maintenance and operation of the tunnel as well as traffic and incident management?
10. What is your business plan for the upgrade or replacement of the equipment and information technology devices, and what do you use to schedule and track their maintenance?
11. How is maintenance or rehabilitation work performed (e.g., under full closure, under partial closure, during specific times of the year)?
12. What details are used to prevent water leakage through the lining, and what remedial measures are taken if there is leakage? How do you handle the effects of corrosion caused by such leaks?
13. Are the lighting and emergency communication systems designed to survive major fires and blasts? If not, what types of mitigations are planned to ensure safe evacuation during an incident that involves major fires or explosions?
14. What are the operational protocols for the use of the ventilation system during a WMD event?

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Harry Capers is the manager of highway, bridge, and tunnel critical infrastructure in the New Jersey Department of Transportation (NJDOT) Office of Transportation Security. He is responsible for coordinating critical infrastructure vulnerability assessment efforts; developing, evaluating, and recommending new security standards and procedures for highways, bridges, and tunnels; and developing and implementing best practices and other highway, bridge, and tunnel transportation security programs for NJDOT. Previously, Capers served as State bridge engineer and manager of the Bureau of Structural Engineering for NJDOT. He was responsible for directing all matters pertaining to highway structures and geotechnical engineering, including bridge management, design and inspection of fixed and moveable bridges, policies and design standards, scopes of work, and capital investments. Capers earned bachelor's and master's degrees in civil engineering from Polytechnic University in Brooklyn, NY, and a master's degree in public administration from Rutgers University in Newark, NJ. He is a licensed professional engineer in New Jersey and New York and a certified public manager in New Jersey. He chairs the AASHTO T–20 Subcommittee on Tunnels and serves on the Subcommittee on Bridges and Structures. He also serves that group as chair of the Loads Committee, vice chair of the Seismic Committee, and a member of the Moveable Bridge and Bridge Security Committees. He chairs the Transportation Research Board (TRB) Committee on General Structures and Subcommittee on Bridge Safety and Security and is a member of the Committee on Bridge Management Systems. Capers has published and presented more than two dozen state-of-the-practice papers on bridge management, construction and design, and transportation security at various conferences in the United States, Japan, and China.

Don Dwyer is an associate soils engineer for the New York State Department of Transportation (NYSDOT). Dwyer is head of the Highway Design and Construction Section, which provides geotechnical support and quality assurance for all NYSDOT projects, from scoping through design and construction. He and his staff also provide geotechnical support and technical assistance for emergency repairs after floods, highway washouts, etc., as well as for routine maintenance. Dwyer is spearheading the beneficial use of recycled materials in highway construction in New York State, including the use of recycled scrap tires. Dwyer has a bachelor's degree in civil engineering from the State University at Buffalo. He is a licensed engineer in New York, and serves on several technical committees of the National Cooperative Highway Research Program (NCHRP), as well as on two technical committees of the AASHTO Subcommittee on Bridges and Structures: T–15 (Substructures and Retaining Walls) and T–20 (Tunnels).

Chris Hawkins is a senior supervising engineer with the engineering firm Parsons Brinckerhoff Quade & Douglas, Inc. Working as project manager and engineer, he has gained broad experience in the design and installation of underground life safety systems and mechanical/electrical support systems. The scope of his work includes metropolitan subway systems, highway tunnels, railroad tunnels, and water/sewage tunnels. He has worked onsite at major underground transportation projects in Europe, Asia, and the United States. This experience encompasses new facility work as well as rehabilitation of existing works. In addition, his design and construction experience includes facility layout, code compliance, cost estimating, equipment selection, and complete contract documents. He has held key positions of responsibility during all phases of underground construction and mining, from conceptual design to project commissioning. Hawkins is a graduate of West Virginia University with a degree in mining engineering and a master's degree in business administration. He is a licensed professional engineer in New York, Massachusetts, and Texas.

Gary Jakovich is a structural engineer with FHWA. Since completing the FHWA Highway Engineer Training Program in 1979, he has been assigned to the Eastern Federal Lands Highway Division in Sterling, VA. As a Bridge Design Team leader, Jakovich is responsible for directing the development of plans and specifications for the construction and rehabilitation of federally owned highway structures in the United States. Over the years, he has participated in the design and construction of numerous projects, including the Linn Cove Viaduct in North Carolina and the Arch Bridge carrying the Natchez Trace Parkway over Tennessee Route 96. His design experience with tunnels has involved the rehabilitation of existing structures on National Park Service roads in Virginia, North Carolina, and Tennessee. He is a graduate of Renssalear Polytechnic Institute and a registered professional engineer in Virginia, and serves as an FHWA liaison to the AASHTO Subcommittee on Bridges and Structures.

Wayne Lupton is the director of maintenance operations for the Colorado Department of Transportation (CDOT). Lupton directs the maintenance and operations programs for CDOT and his responsibilities include emergency preparedness coordination for CDOT. In the past, he was the maintenance superintendent for the Hanging Lake Tunnels in Glenwood Springs, CO. During his 31-year tenure with CDOT, Lupton has used different types of highway maintenance techniques, including 6 years of tunnel maintenance and operations. Lupton has been involved in the use of intelligent transportation system (ITS) technologies for the past 11 years. He has worked on FHWA's Lead State program, two Highway Innovative Technology Evaluation Center panels, and FHWA's Peer-to-Peer Program for ITS, and is now on three NCHRP panels. He holds degrees in electronic technology and computer maintenance.

Tom Margro is the general manager of the Bay Area Rapid Transit District (BART). Margro is responsible for managing the entire BART rapid transit (heavy rail) system, which encompasses 169 route kilometers (105 route miles) and 43 stations and carries more than 300,000 passengers daily. Before becoming general manager, he was assistant general manager of transit system development, responsible for implementing the BART Extensions Program. Before coming to BART, Margro was with the Southeastern Pennsylvania Transportation Authority for 18 years, working in engineering, operations, and capital projects. During his time with the authority, he served as manager of facilities engineering, senior program manager of electrical facilities, chief engineer, and assistant general manager of engineering and construction. He also worked for the New Jersey Turnpike Authority, where he was director of maintenance and engineering services and chief engineer. Margro has a bachelor's degree in electrical engineering from Syracuse University and a master's degree in systems engineering from the University of Pennsylvania. He also completed additional postgraduate studies in systems engineering. He is a registered professional engineer in New Jersey and Pennsylvania and has served on several American Public Transportation Association (APTA) committees.

Mary Lou Ralls *(report facilitator)* is an engineering consultant and principal of Ralls Newman, LLC in Austin, TX, specializing in the advancement of structural engineering technologies including accelerated construction and transportation security. Before becoming an independent consultant in late 2004, Ralls was a structural engineer with the Texas Department of Transportation for 20 years, the last 5 years as State bridge engineer and director of the bridge division. In this position, Ralls was a member of the AASHTO Highway Subcommittee on Bridges and Structures and was chair of the Technical Committee for Security and vice chair of the Technical Committee for Research. She was also a member of the AASHTO Task Force on Transportation Security. Ralls earned her bachelor's and master's degrees in civil engineering from The University of Texas at Austin in 1981 and 1984, respectively, and became a licensed professional engineer in Texas in 1987. Since 2003, Ralls has served as chair of the TRB Structures Section, which includes the Tunnels and Underground Structures Committee, and is a member of the TRB Critical Transportation Infrastructure Protection Committee. She is also a member of several NCHRP panels on transportation structures and security.

Jesus M. Rohena is the senior tunnel engineer for the FHWA Office of Bridge Technology in Washington, DC. Rohena is responsible for managing FHWA's Federal-aid tunnel program for all States, the District of Columbia, and Puerto Rico. Before joining the Office of Bridge Technology in 2005, he served as the complex structures specialist at the FHWA Resource Center in Baltimore, MD. Rohena has worked with FHWA in the field of tunnel engineering since 1990. He has a bachelor's degree in civil engineering from the University of Puerto Rico and a master's degree in structural engineering from the George Washington University in Washington, DC. He is a licensed professional engineer in Virginia. He serves on the TRB Tunnels and Underground Structures Technical Committee, and is a member of the National Fire Protection Association (NFPA), the World Road Association (PIARC) Technical Committee C3.3 on Road Tunnel Operation, and the International Tunneling Association (ITA). He serves as an FHWA liaison to the AASHTO Subcommittee T–20 on Tunnels.

Michael W. Swanson is the chief operating officer and chief engineer of the Massachusetts Turnpike Authority (MTA), where he is responsible for managing the Engineering, Construction, Toll Collection, and Maintenance Divisions and the activities of Troop E of the Massachusetts State Police. Swanson directed the transition process for Boston's Central Artery/Tunnel Project to ensure that all Central Artery elements turned over to MTA for operation, maintenance, and ownership were constructed properly and that the facilities were safe to open and operate. He also directed the staffing assessments necessary to ensure that MTA had the human and equipment resources necessary to safely operate the new tunnel and highway elements. From 1993 to 1996, Swanson served as the deputy secretary for capital and transportation planning, where he managed the capital and transportation planning programs of the Executive Office of Transportation and Construction. He is a registered engineer in Massachusetts.

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Publication No. FHWA-PL-06-016
HPIP/1-06(3.5)EW