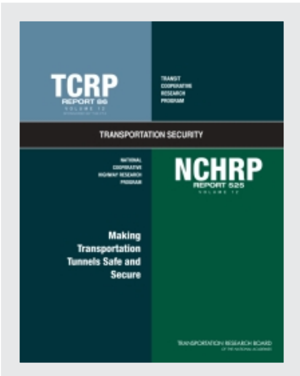

Making Transportation Tunnels Safe and Secure

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Transportation Research Board

TRANSIT COOPERATIVE RESEARCH PROGRAM
AND
NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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TRANSPORTATION SECURITY

Volume 12:

Making Transportation Tunnels Safe and Secure

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TRANSPORTATION RESEARCH BOARD

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TRANSIT COOPERATIVE RESEARCH PROGRAM

The nation's growth and the need to meet mobility, environmental, and energy objectives place demands on public transit systems. Current systems, some of which are old and in need of upgrading, must expand service area, increase service frequency, and improve efficiency to serve these demands. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. The Transit Cooperative Research Program (TCRP) serves as one of the principal means by which the transit industry can develop innovative near-term solutions to meet demands placed on it.

The need for TCRP was originally identified in *TRB Special Report 213—Research for Public Transit: New Directions,* published in 1987 and based on a study sponsored by the Urban Mass Transportation Administration—now the Federal Transit Administration (FTA). A report by the American Public Transportation Association (APTA), Transportation 2000, also recognized the need for local, problem-solving research. TCRP, modeled after the longstanding and successful National Cooperative Highway Research Program, undertakes research and other technical activities in response to the needs of transit service providers. The scope of TCRP includes a variety of transit research fields including planning, service configuration, equipment, facilities, operations, human resources, maintenance, policy, and administrative practices.

TCRP was established under FTA sponsorship in July 1992. Proposed by the U.S. Department of Transportation, TCRP was authorized as part of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). On May 13, 1992, a memorandum agreement outlining TCRP operating procedures was executed by the three cooperating organizations: FTA, the National Academies, acting through the Transportation Research Board (TRB); and the Transit Development Corporation, Inc. (TDC), a nonprofit educational and research organization established by APTA. TDC is responsible for forming the independent governing board, designated as the TCRP Oversight and Project Selection (TOPS) Committee.

Research problem statements for TCRP are solicited periodically but may be submitted to TRB by anyone at any time. It is the responsibility of the TOPS Committee to formulate the research program by identifying the highest priority projects. As part of the evaluation, the TOPS Committee defines funding levels and expected products.

Once selected, each project is assigned to an expert panel, appointed by the Transportation Research Board. The panels prepare project statements (requests for proposals), select contractors, and provide technical guidance and counsel throughout the life of the project. The process for developing research problem statements and selecting research agencies has been used by TRB in managing cooperative research programs since 1962. As in other TRB activities, TCRP project panels serve voluntarily without compensation.

Because research cannot have the desired impact if products fail to reach the intended audience, special emphasis is placed on disseminating TCRP results to the intended end users of the research: transit agencies, service providers, and suppliers. TRB provides a series of research reports, syntheses of transit practice, and other supporting material developed by TCRP research. APTA will arrange for workshops, training aids, field visits, and other activities to ensure that results are implemented by urban and rural transit industry practitioners.

The TCRP provides a forum where transit agencies can cooperatively address common operational problems. The TCRP results support and complement other ongoing transit research and training programs.

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The project that is the subject of this report was a part of the Transit Cooperative Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the project concerned is appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical advisory panel selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and while they have been accepted as appropriate by the technical panel, they are not necessarily those of the Transportation Research Board, the National Research Council, the Transit Development Corporation, or the Federal Transit Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical panel according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

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

NCHRP REPORT 525, VOLUME 12

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The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

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CRP STAFF FOR TCRP REPORT 86/NCHRP REPORT 525, VOL. 12

TCRP PROJECT J-10G PANEL/NCHRP PROJECT 20-67 PANEL
TCRP Field of Special Projects
NCHRP Field of Special Projects

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FOREWORD

By S. A. Parker
Staff Officer
Transportation Research Board

This twelfth volume of both *NCHRP Report 525: Surface Transportation Security* and *TCRP Report 86: Public Transportation Security* is designed to provide transportation tunnel owners and operators with guidelines for protecting their tunnels by minimizing the damage potential from extreme events such that, if damaged, they may be returned to full functionality in relatively short periods. This report will be of interest to tunnel authorities, state and local transportation departments, other agencies responsible for tunnel operation and maintenance, enforcement personnel and first responders responsible for tunnel safety and security, and tunnel designers.

The objective of *Volume 12: Making Transportation Tunnels Safe and Secure* is to provide safety and security guidelines for owners and operators of transportation tunnels to use in identifying (1) principal vulnerabilities of tunnels to various hazards and threats; (2) potential physical countermeasures; (3) potential operational countermeasures; and (4) deployable, integrated systems for emergency-related command, control, communications, and information.

These guidelines were developed jointly under TCRP and NCHRP. They are appropriate for all modes of transportation.

Science Applications International Corporation, together with Parsons Brinckerhoff Quade & Douglas, Inc., and Interactive Elements, Inc., prepared this volume of *NCHRP Report 525/TCRP Report 86* under NCHRP Project 20-67/TCRP Project J-10G.

Emergencies arising from terrorist threats highlight the need for transportation managers to minimize the vulnerability of travelers, employees, and physical assets through incident prevention, preparedness, mitigation, response, and recovery. Managers seek to reduce the chances that transportation vehicles and facilities will be targets or instruments of terrorist attacks and to be prepared to respond to and recover from such possibilities. By being prepared to respond to terrorism, each transportation agency is simultaneously prepared to respond to natural disasters such as hurricanes, floods, and wildfires, as well as human-caused events such as hazardous materials spills and other incidents.

This is the twelfth volume of *NCHRP Report 525: Surface Transportation Security* and the twelfth volume of *TCRP Report 86: Public Transportation Security,* two series in which relevant information is assembled into single, concise volumes—each pertaining to a specific security problem and closely related issues. These volumes focus on the concerns that transportation agencies are addressing when developing programs in response to the terrorist attacks of September 11, 2001, and the anthrax attacks that followed. Future volumes of the reports will be issued as they are completed.

To develop this volume in a comprehensive manner and to ensure inclusion of significant knowledge, available information was assembled from numerous sources, including a number of state departments of transportation. A topic panel of experts in the subject area was established to guide the researchers in organizing and evaluating the collected data and to review the final document.

This volume was prepared to meet an urgent need for information in this area. It records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. Work in this area is proceeding swiftly, and readers are encouraged to be on the lookout for the most up-to-date information.

Volumes issued under *NCHRP Report 525: Surface Transportation Security* and *TCRP Report 86: Public Transportation Security* may be found on the TRB website at http://www.TRB.org/SecurityPubs.

CONTENTS

Disclaimer: The contents within these guidelines reflect the best judgment and experience of Parsons Brinckerhoff Quade & Douglas, Inc. (PB), Science Applications International Corporation (SAIC), and Interactive Elements, Inc. (IEI), who researched and developed this book. The principal investigator for this project was Irfan Oncu (PB). Primary authors were Kevin A. Duffy (SAIC), Jaw-Nan (Joe) Wang (PB), Arthur Bendelius (PB), Gloria Hettinger (PB), Steve Lockwood (PB), Harry Saporta (PB), James Guinan (PB), and Dorothy Schulz (IEI).

PREFACE

This research project aimed to provide safety and security guidelines for transportation tunnel owners and operators. To accomplish this task, a team of experienced tunnel designers, builders, and operations personnel collaborated with safety and security experts to address the questions that a tunnel owner or operator may face in the post-9/11 environment, including the following:

- What natural hazards and intentional threats do I face?
- How would they be introduced?
- What are the vulnerable areas of my tunnel?
- How much of a disturbance would there be?
- How can I avoid these hazards and threats?
- How can I prepare myself for this disturbance if it occurs?

While risks to tunnels derive from both intentional threats related to crime and terrorism and hazards related to natural (i.e., unintentional) events, the risks often have the same tunnel vulnerabilities and damage potential and may share common countermeasures. Therefore, in this report, threat- and hazard-related characteristics and countermeasures are typically treated together in text and tables, except where specifically noted.

The recommendations for countermeasures presented in this report are intended for implementation by the tunnel owner or operator. This implementation may occur in part or whole depending on the local conditions and, importantly, the level of risk faced by the owner or operator. The owner or operator will also need to balance the implementation of structural and/or operational countermeasures with funding constraints. The countermeasures are presented as a menu of items that the owner or operator may select from. Issues of funding are not extensively explored in this report.

This report is organized into seven chapters:

- **Chapter 1, "Introduction,"** introduces the problems that this project has attempted to solve and the environment of the work. The chapter also describes the assumptions of the research team in approaching the work and defines the research terms.
- **Chapter 2, "Hazards and Threats,"** describes hazards and threats according to the areas or elements of the tunnel that might be affected, how the hazards and threats might be introduced, the operational and physical vulnerabilities to those hazards and threats, and the damage potential of the hazards and threats.
- **Chapter 3, "Case Studies,"** provides a chronology of past tunnel disasters that were studied for this project. The case studies researched the cause and effect of the disasters to glean pertinent information that may be applied in this research.
- **Chapter 4, "Tunnel Elements and Vulnerabilities,"** gives basic descriptions of various tunnel types, both by mode of transportation and by construction methodology. The chapter then outlines specific vulnerabilities by describing how and why failures can occur under safety- and security-related hazards and threats (e.g., fire or explosion) based on characteris-

tics of the tunnel's structure as well as the surrounding earth. The chapter rates the damage potential for various types of tunnels under explosion and fire events. The chapter also summarizes structural vulnerabilities and damage potential of the most extreme hazard or threat scenarios for road, transit, and rail tunnels.

The chapter presents a parallel analysis for mechanical, electrical, and communications (MEC) systems serving tunnels. These systems are described and categorized based on how critical they are to the continuing functionality of the tunnel and on the impact that system disruption would have. The chapter rates vulnerability versus critical location for the five MEC system types deemed to be the most critical. The system vulnerabilities and damage potential of the most extreme hazard and threat scenarios are summarized for road, transit, and rail tunnels.

- **Chapter 5, "Countermeasures,"** presents structural and system hazard and threat directories, in the form of tables, that summarize the information given in Chapter 4. The tunnel owner or operator is instructed how to apply these directories to his or her own facility and, by the process of elimination, identify which of eight countermeasure guides to consult. The countermeasure guides, which are also presented in the form of tables, refer the user to 50 possible countermeasures. The countermeasures are physical and/or operational methods for improving the structural and/or system elements of the tunnel. Within the guides, each countermeasure is supplied with the following:
  - Implementation (i.e., minimum required, deployed for an elevated threat level, or permanent enhancement),
  - Function and description,
  - Relative effectiveness,
  - Order-of-magnitude cost,
  - Physical or operational in nature,
  - Security strategy (i.e., deter, detect, interdict, or mitigate, including response and preparedness), and
  - Multiple-benefit potential.

  Directly following the guides, the 50 countermeasures are described in detail and are accompanied by sketches wherever possible. The countermeasure descriptions incorporate limitations of existing tunnels, types of construction, materials used, and the current tunnel environmental conditions. The recommendations are intended to improve the operational safety and structural integrity of the tunnel when exposed to a hazard or threat.
- **Chapter 6, "System Integration,"** provides information on current and proposed integrated systems that may be used to increase the safety and security of a transportation tunnel.
- **Chapter 7, "Future Research,"** provides recommendations for areas requiring further study and approximate funding costs. The areas of future research include 26 items with various cost and schedule estimates.

The report concludes with a list of references that were cited in the text, a list of additional sources, and a list of abbreviations.

CHAPTER 1

Introduction

It is estimated that there are 337 highway tunnels and 211 transit tunnels in the United States [Ref. 1]. These tunnels move thousands of people and tons of cargo daily. Many of these tunnel facilities are located at key "choke points" in the nation's transportation network. As with other components of the transportation infrastructure, tunnels are susceptible to a range of hazards and threats.

Tunnels can face disruption from either the occurrence of hazards (i.e., unintentional, accidental events) or the successful conduct of threats (i.e., intentional acts). Hazards can be human- or equipment-related (e.g., motor vehicle collisions and resulting fire) or natural (e.g., flooding and earthquakes). Relatively new tunnels have allowances for natural disasters incorporated into their design and construction. The allowances are based on the best engineering practices. Although older tunnels may lack some features that are commonplace in modern design and construction, the older tunnels may still be quite serviceable. Whether old or new, some tunnels may be impregnable to natural disaster because of their location, but still vulnerable to incidents.

Threats resulting in intentional disruption can include terrorist attacks such as those that occurred on September 11, 2001. While tunnels and transportation facilities were not the primary targets of those attacks, there were certainly numerous secondary effects on the transportation system. Tunnels make tempting targets because (a) they are important to the economic viability of surrounding communities, especially when they are used to transport goods; (b) many people are present at predictable times; and (c) the enclosed environment further compounds the potential for casualties from the effects of confined blast events, collapse, and flooding. Transit tunnels, in particular, are easily reached from open, accessible environments (i.e., stations); as a result, these tunnels are viewed as high-risk, high-damage potential targets. Examples of intentional, harmful aggression against transit tunnel environments and users are the 1995 sarin gas attack in Tokyo, the 2003 arson fire in Daegu, and the 2004 bombing in Moscow. The traveling public relies on the security and safety of transportation tunnels on a daily basis. It is essential that steps be taken to protect these important assets.

From a policy perspective, tunnel managers have two significant concerns. First, tunnels serve important day-to-day transportation functions, often providing nonredundant network connections. Second, owners must plan for effective use of the tunnels to transport people and goods as emergency relief in the event of severe emergencies occurring elsewhere. For example, an approaching hurricane in a coastal area may necessitate use of a highway tunnel for mass evacuation if it is deemed safe to do so. Alternatively, as on September 11, the initial closing of the transit and highway tunnels leading out of Manhattan required thousands of people to walk across outbound bridges. Even less catastrophic events, such as traffic accidents or train derailments, may have rippling effects in other parts of the transportation system. Moreover, extreme events will invariably impact multiple modes and other local, state, or national resources.

Because tunnels are expensive to build and operate, the existence of a tunnel usually indicates that no feasible alternatives existed; thus, no alternate routing or means of transport in the event of disrupted operation is likely to exist. In recognition of tunnels' vital roles and their exposure to harmful disruption, transportation tunnel security and safety issues have become part of the national security dialogue.

This report provides tunnel owners and operators with guidelines for protecting their tunnels to minimize the damage potential from extreme events so that, if damaged, the tunnels may be returned to full functionality in relatively short periods.

The report focuses on three kinds of transportation tunnels: highway, rail, and transit. Rail (which includes both passenger and freight) and transit tunnels are separate categories. Rail tunnels are typically larger and can carry greater loads than transit tunnels. Transit lines are typically in urban areas, with smaller and shorter cars, slower speeds, shorter distances, and higher occupancies than passenger rail lines.

1.1 Audience

The anticipated audience for these guidelines includes the following:

- Tunnel authorities or asset owners,
- State and local transportation departments and agencies responsible for tunnel operation and maintenance,
- Enforcement personnel and first responders responsible for tunnel safety and security, and
- Tunnel design consultants.

1.2 Basic Definitions

The basic concepts of risk management involve the relationships among (a) the nature of the threat or hazard that can cause damage to a susceptible asset, (b) the asset's operational and physical vulnerabilities to attack and/or failure, and (c) the damage potential (consisting of the loss of use of that asset and the loss of benefit of that asset to users).

Understanding relevant terminology is critical for all-hazards risk management and countermeasure strategy development. Most important is the distinction between hazards, which are unintentional, and threats, which are intentional. Neither of these terms implies a probability or likelihood that the event will materialize unless the terms are modified with explicit probability descriptors. The following definitions are used in this report:

- **Hazard—**The potential *unintentional* condition or event capable of disrupting or negatively impacting an asset, such as fire, power loss, or equipment breakdown. Hazards are usually associated with natural events and safety and are often measured in terms of the frequency and magnitude of the event. Hazards can also include degradation of structural integrity.
- **Threat—**The potential *intentional* act capable of disrupting or negatively impacting an asset. In other words, threats are deliberate attempts of a person or group to achieve various criminal or terrorist ends that may involve loss of life, loss of function, loss of visibility, and other objectives.

  Threats are distinct from hazards because they are not acts of nature, accidents, or organic happenstances for which tunnels are normally designed. Rather, threats are typically characterized as acts of intrusion; placement of explosive devices; and/or chemical, biological, or radiological attacks. In the case of terrorism, a threat consists of a scenario that combines a weapon, a host (i.e., an aggressor), a delivery mode, and tactics (i.e., a path of approach, the use of stealth or force, and the actual target of weapon placement). While hazards are associated with safety, threats are associated with security.
- **Target/Asset—**Persons, facilities, activities, or physical systems that have value to the owner or to society as a whole.
- **Damage Potential—**The potential for negative effects—including immediate and long-term damage or loss, whether tangible or intangible—resulting from an unintentional event or an attack on an asset. Mission-related damage potential (i.e., impacts that are critical to the owner's transportation institutional mission, including destruction or damage causing loss or reduction of functionality) is of special importance, together with injury or loss of life, as well as impacts on quality of life and morale. Damage potential grows as a function of an asset's criticality. However, a critical asset may be damaged without a total loss of functionality.
- **Vulnerability—**A weakness in asset design or operations that can be exploited by a threat or hazard to produce negative consequences, or damage. Specific threats and hazards therefore relate to different vulnerabilities.

It should be noted that the specific quantitative relationship among the variables in the risk equation depends on how the various factors are developed and expressed. For example, damage potential and vulnerability of assets can be judged on a relative scale with upper and lower bounds or through analytical models that assess asset criticality in terms of potential casualties, economic impacts, or physical or operational vulnerabilities. However, the probability of a threat or hazard materializing to trigger the consequences may be difficult to estimate in more than qualitative or relative terms.

1.3 Methodology

Vulnerability and damage potential have been ranked on relative scales and analyzed to develop priorities for countermeasures.

1.4 Assumptions

This report was prepared using the collective knowledge and experience of the authors. Common sense was used to avoid unnecessary duplication of effort; further exploration of common topics encountered by a tunnel owner or operator; and improbable hazard and threat situations, damage potential, and countermeasures.

The single most significant assumption made during this research effort is that guidelines that cover the range of "routine" hazards to tunnel safety—such as equipment breakdowns, derailments, utility disruptions, minor criminal acts, and medical emergencies—already exist. The experience of tunnel operators in handling these minor incidents is already addressed in handbooks, manuals, and industry standards that are readily available. Wherever possible, references to these materials are noted in the text. The addition of security-related threats—from both major criminal acts and terrorism—then becomes an important extension to an "all-hazards" approach to tunnel security.

The research did not address nuclear threats, common natural or weather hazards, or inspection or maintenance issues.

Additional assumptions include the following:

- The physical aspects of the tunnel (i.e., structural aspects, geotechnical aspects, and water levels) are known before the tunnel owner or operator uses this guide.
- Before implementing any of the countermeasures recommended herein, the tunnel owner or operator will conduct a full engineering assessment that takes into account facility-specific conditions.

CHAPTER 2

Hazards and Threats

Tunnel systems, in their design, have a safe environmental order and are capable of withstanding the assaults normally presented by everyday use. For example, below-grade tunnels are watertight, with proper water evacuation capability and safety systems to move air into and out of the tubes. The tunnel structure is designed and built to exist within the soil or seabed that it occupies. Mined tunnels similarly coexist within their surface environment to provide safe, smooth operation. Despite these and other safety features, however, damage or disruption to a tunnel, its operations, and/or occupants can result from the impact of hazards or threats.

The tables in this chapter consist of a list of major hazards and threats that may adversely impact the normal operation of a transportation tunnel and associated infrastructure. The transportation tunnel and associated infrastructure include all electrical and mechanical operations within the tunnel environment, such as ventilation and fire suppression. Hazards and threats to the tunnel environment also include actual or perceived physical hazards and threats affecting the users of the transportation system.

The primary criterion used for the analysis of safety hazards and security threats was the level of impact that a major hazard or threat would have on the tunnel system. All hazards and threats considered in depth are capable of closing a tunnel for an extended period of time (i.e., lasting more than 25 hours). These hazards and threats encompass potential incidents that have not been routinely encountered or planned for by a tunnel operator.

Because the standard literature discusses hazard issues, threats make up the major portion of the events examined in this report, particularly threats related to the introduction of a foreign item into the tunnel environment to disrupt the tunnel and its users. This analysis excludes completely the range of safety hazards that are routinely observed and handled by a tunnel operator—such as equipment breakdown, utility disruptions, minor criminal acts, and medical emergencies—because tunnel operators have years of experience in handling such issues. The experiences of tunnel operators in handling these minor incidents have been distilled into handbooks and readily available procedural reference materials. Where possible, notations for additional reference material concerning these minor hazards have been included in this report.

The focus of this guidance is, therefore, a combination of major hazards that are not likely and threats—principally acts of terrorism—that might be realized in a tunnel environment. Unlikely, extraordinary threats have been excluded. These include highly unlikely acts of terrorism that seem irrational or ineffective in a tunnel context (such as a nuclear detonation or airborne threats).

The hazards and threats discussed in this report have been assembled individually. With this format, the reader can first absorb the details of each potential scenario and then read the recommended actions to mitigate the hazard or threat.

The remainder of Chapter 2 discusses (a) the major hazards and threats that will adversely affect the normal operation of a transportation tunnel and its associated infrastructure, (b) the damage potential of these hazards and threats, and (c) possible hazard and threat scenarios.

2.1 Major Hazards and Threats

Table 1 presents a range of major hazards and threats that may adversely affect a tunnel and its associated features. The hazards and threats are expressed in terms of generic scenarios with potential to damage the normal operation of a transportation system, including specific tunnel components.

One of the concerns, “Fire,” appears under the “Threat” heading as arson and under the “Hazard” heading as unintentional. This distinction is made because, although the

Table 1. Major hazards and threats to transportation tunnels and associated features.

Hazard or Threat	Vulnerable Tunnel Feature									
	Tunnel Construction and Engineering Feature						Tunnel System Feature			
	Immersed Tube	Cut-and-Cover	Bored or Mined	Vent Shaft	Portal	Station	Distribution Channel	Control Center	Substation	Utility Building
Hazard										
Fire (Unintentional)	√	√	√	√	√	√	√	√	√	√
Structural Integrity Loss by Natural Causes	√	√	√	√	√	√	√	√	√	
Introduction of Hazardous Materials	√	√	√	√	√	√				
Threat										
Introduction of Small IEDs	√	√	√	√		√	√	√	√	√
Introduction of Medium-Sized IEDs	√	√	√	√	√	√	√	√	√	√
Introduction of Large IEDs	√	√	√	√	√	√	√	√	√	√
Introduction of Chemical Agents				√		√				
Introduction of Biological Agents				√		√				
Introduction of Radiological Agents	√	√	√		√	√				
Cyber Attack								√		
Maritime Incident	√		√							
Fire (Arson)	√	√	√	√	√	√	√	√	√	√
Sabotage of MEC Systems	√	√	√	√		√	√	√	√	√

IEDs = improvised explosive devices.
MEC = mechanical, electrical, and communications.

effects of an intentional fire and an unintentional fire may be similar, the defenses to the two kinds of fire may differ.

There are three major hazards and 10 major threats. The major hazards are the following:

- Fire (unintentional),
- Structural integrity loss by natural causes, and
- Introduction of hazardous materials.

The major threats are the following:

- Introduction of small improvised explosive devices (IEDs): explosive materials delivered via one to five aggressors transporting the payload.
- Introduction of medium-sized IEDs: explosive materials delivered either by vehicle (car) or by multiple persons acting in concert to transport the payload.
- Introduction of large IEDs: explosive materials delivered either by vehicle (truck) or by multiple persons acting in concert to transport the payload.
- Introduction of chemical agents.
- Introduction of biological agents.
- Introduction of radiological agents.
- Cyber attack: a virtual aggression against the command and control systems of a tunnel system with the intent of disabling systems.
- Maritime incident: a waterborne incident affecting a tunnel shell from above and any exposed sides. Adverse

impacts may be due to sunken ships, misguided anchors, or explosives.
- Fire (arson): an intentionally set conflagration with the intent of causing physical harm or damage to property.
- Sabotage of mechanical, electrical, and communications (MEC) systems: the intentional impairment or destruction of MEC systems necessary to the safe, efficient operation of a tunnel system.

The right side of the table notes the affected vulnerable tunnel features, also referred to in this report as "assets." The vulnerable tunnel features have been divided into two types: tunnel construction and engineering features and tunnel system features.

Tunnel construction and engineering features include the type of tunnel facility constructed and the major engineered features, which are typically immovable. There are six categories of tunnel construction and engineering features:

- Immersed tube: employed to traverse a body of water. Tunnel sections, usually 300 to 450 feet (91 to 137 meters) long, are placed into a pre-excavated trench.
- Cut-and-cover: tunnel construction method involves braced, trench-type excavation ("cut") construction of structures and placement of fill materials over the finished structures ("cover").
- Bored or mined: bored tunnels are often excavated using mechanical equipment such as road headers or tunnel boring machines (TBMs), while mined tunnels may be excavated using manual or mechanical methods.
- Vent shaft: any at-surface or above-grade air intake or exhaust facility servicing a below-grade road, transit, or rail section.
- Portal: any engineered entranceway or boat section to a below-grade road, transit, or rail section.
- Station: any facility in regular use by nonemployees of a passenger rail or transit system. Unlike the other categories of construction and engineering features, this category is applicable to passenger rail and transit only.

Tunnel system features include the major components designed and installed to support the efficient operation and safe environment of a tunnel. Mechanical, electrical, ventilation, and communication systems are the major sections designed to support the tunnel system. These systems are capable of update or replacement over time. The categories of tunnel system features are as follows:

- Distribution channel: any conduit, sheath, piping, fiber optic, or metal line designed and installed to provide a source of power or method of communication between a tunnel system and a utility terminus.
- Control center: any facility designed, constructed, and equipped with systems intended to monitor and control the tunnel environment and the movement of vehicle and rail traffic over and through a tunnel section.
- Substation: any facility specifically designed to relay power, water, or sewer connections between the tunnel and the central utility building. The substation is connected to the utility building and the tunnel via distribution channels.
- Utility building: Any facility specifically designed to provide power to the tunnel system. This facility is operated continuously to achieve its mission and is connected to both substations and the tunnel through a distribution channel. A utility building may also be designed to provide water or sewer removal from the tunnel.

2.2 Damage Potential

The damage potential of hazard and threat scenarios—often a sequence of physical events (such as fire or flooding) and their secondary impacts (such as injuries, fatalities, or loss of function)—determines the key characteristics of countermeasures that can mitigate the impact of hazards and threats, if not prevent them. Table 2 presents the damage potential of the hazards and threats listed in Table 1.

Except for radiation, the types of damage listed in Table 2 and considered throughout this report are visible to emergency responders and the tunnel operator. All types of damage, including radiation, may be mitigated. Possible damage includes the following:

- Fire/smoke: any active conflagration or post conflagration condition of smoke and harmful vapors.
- Flooding: the condition of excessive water inflow to a tunnel area exceeding the pumping capacity of the tunnel systems and causing a hazard or threat to people and property.
- Structural integrity loss: any decrease in the fitness of the tunnel to carry passengers or freight that requires inspection by the tunnel owner and major repair prior to its reopening for beneficial use by the public.
- Contamination: the condition of being unfit for normal habitation due to the presence of radiation, biological agents, harmful chemicals, hazardous airborne particles, or sewage sufficient to require professional remediation.
- Utility disruption: loss of power, air, steam, water, or communication service for more than 25 hours.

Table 2. Damage potential of hazards and threats.

Hazard or Threat	Damage Potential						
	Fire/Smoke	Flooding	Structural Integrity Loss	Contamination	Utility Disruption	Extended Loss of Asset Use	Extended Public Health Issue
Hazard							
Fire (Unintentional)	√	√	√	√	√	√	√
Structural Integrity Loss by Natural Causes	√	√	√	√	√	√	√
Introduction of Hazardous Materials				√		√	√
Threat							
Introduction of Small, Medium-Sized, or Large IEDs	√	√	√	√	√	√	√
Introduction of C/B/R Agents				√		√	√
Cyber Attack						√	
Maritime Incident		√	√			√	
Fire (Arson)	√	√	√	√	√	√	√
Sabotage of MEC Systems	√	√	√	√	√	√	√

C/B/R = chemical/biological/radiological.
IEDs = improvised explosive devices.
MEC = mechanical, electrical, and communications.

- Extended loss of asset use: loss of the ability to safely move passengers or allow vehicular traffic for more than 25 hours.
- Extended public health issue: actual or potential ability to cause illness in a significant portion of the population sufficient to overwhelm the medical treatment capacity of the area.

2.3 Hazard and Threat Scenarios

Hazard and threat scenarios are profiles that include the hazard or threat, the mode of delivery, the path to the target, the tactical delivery device, and the location of the target. Table 3 provides basic hazard and threat scenarios. The assumptions made during the development of this table are based on past terrorist acts and current available intelligence. The scenarios are intended to include categories applicable to highway, rail, and transit tunnel systems. However, the needs, vulnerabilities, and points of access differ from mode to mode, as well as from tunnel to tunnel within a mode. The reader is encouraged to review the text to ascertain the applicability of the table to his or her own situation.

The following sections present hazard and threat scenarios, respectively, in relation to assets. Note that some scenarios, such as fire, may be the result of an intentional act (i.e., a threat) or an unintentional event or circumstance (i.e., a hazard).

2.3.1 Hazard Scenarios in Relation to Assets

Fire (Unintentional)

Unintentional fire is more probable than intentional fire and has occurred in several tunnel systems. Fire may destroy any structure or vehicle and kill people if not controlled. A tunnel structure may be completely ruined by a conflagration. Fire sources may be disparate and triggered by any combination of flammable material and ignition. Fire occurs in nature and does not necessarily require human intervention to spread. Fire, or the danger of fire as a smoke condition, will immediately have a negative impact on all tunnel assets by inducing the evacuation of persons and equipment from

Table 3. Hazard and threat scenarios.

Hazard or Threat	Mode of Delivery	Path to Target	Tactical Delivery Device	Location of Target
Very Large IED	Ship	Waterway	Explosive Container (Depth Charge)	Top of Tunnel
Large IED	Vehicle	Tunnel Roadway	Truck	Liner
Large IED	Vehicle	Tunnel Roadway	Truck	Column or Wall
Large IED	Vehicle	Surface Roadway over Tunnel	Truck	Roof Slab
Large IED	Vehicle	Tunnel Roadway	Truck	Ventilation Building
Large IED	Vehicle	Surface Access Road	Truck	Ventilation Building
Large IED	Vehicle	Tunnel Roadway	Truck	C&C Center Above Tunnel
Large IED	Vehicle	Surface Access Road	Truck	Stand-Alone C&C Center
Large IED	Vehicle	Surface Access Road	Truck	Stand-Alone Substation
Large IED	Vehicle	Surface Access Road	Truck	Ventilation Shaft
Large IED	Vehicle	Surface Access Road	Truck	Station
Large IED	Vehicle	Surface Access Road	Truck	Ventilation Structure
Large IED	Rail or Transit Vehicle	Trackway	Locomotive or Freight/ Passenger Car	Liner
Large IED	Rail or Transit Vehicle	Trackway	Locomotive or Freight/ Passenger Car	Column or Wall
Medium IED	Vehicle	Tunnel Roadway	Car or Van	Liner
Medium IED	Vehicle	Tunnel Roadway	Car or Van	Column or Wall
Medium IED	Vehicle	Tunnel Roadway	Car or Van	Ventilation Building
Medium IED	Vehicle	Surface Access Road	Car or Van	Ventilation Building
Medium IED	Vehicle	Tunnel Roadway	Car or Van	C&C Center Above Tunnel
Medium IED	Vehicle	Surface Access Road	Car or Van	Stand-Alone C&C Center
Medium IED	Vehicle	Surface Access Road	Car or Van	Stand-Alone Substation
Medium IED	Vehicle	Surface Access Road	Car or Van	Ventilation Shaft
Medium IED	Vehicle	Surface Access Road	Car or Van	Ventilation Structure
Medium IED	Motor Vehicle or Foot	Surface Roadway over Tunnel	Truck or Multiple Backpacks	Roof Slab
Medium IED	Transit Vehicle	Trackway	Car or Engine	Liner
Medium IED	Transit Vehicle	Trackway	Car or Engine	Column or Wall
Medium IED	Rail Car or Foot	Trackway	Freight/Passenger Car, Engine, or Multiple Backpacks	Liner
Medium IED	Rail Car or Foot	Trackway	Freight/Passenger Car, Engine, or Multiple Backpacks	Column or Wall
Small IED	Foot	Tunnel Roadway	Backpack	Liner
Small IED	Foot	Tunnel Roadway	Backpack	Column or Wall
Small IED	Foot	Stations/Shops/ Tunnel Portals	Backpack	Column or Wall
Small IED	Foot	Stations/Shops/ Tunnel Portals	Backpack	Liner

Table 3. (Continued).

Hazard or Threat	Mode of Delivery	Path to Target	Tactical Delivery Device	Location of Target
Small IED	Foot	Tunnel Roadway	Backpack	Exposed Ductbank
Small IED	Foot	Surface Access Road	Backpack	Inside Ventilation Building
Small IED	Foot	Surface Access Road	Backpack	Inside C&C Center
Small IED	Foot	Surface Access Road	Backpack	Inside a Stand-Alone Substation
Small IED	Foot	Tunnel Trainway	Backpack	Exposed Ductbank or MEC Equipment
Small IED	Foot	Tunnel Trainway	Transit Vehicle	Station
Small IED	Foot	Surface Access Road	Backpack	Station
Small IED	Foot	Surface Access Road	Backpack	Inside Substation
Small IED	Foot	Surface Access Road	Backpack	Inside Ventilation Structure
Large Fire	Vehicle	Tunnel Roadway	Tanker	Liner
Large Fire	Vehicle	Tunnel Roadway	Tanker	Column/Wall/Roof Slab
Large Fire	Vehicle	Tunnel Roadway	Tanker	Portal
Large Fire	Vehicle	Tunnel Roadway	Tanker	Any Tunnel Location Adjacent to Critical Facility
Large Fire	Rail/Transit Car	Trackway	IED on Train	Liner
Large Fire	Rail/Transit Car	Trackway	IED on Train	Column/Wall/Roof Slab
Large Fire	Rail/Transit Car	Trackway	IED on Train	Portal
Large Fire	Rail/Transit Car	Trackway	IED on Train	Any Tunnel Location Adjacent to Critical Facility
C/B/R	Foot	Tunnel Air Supply System	Vial/Aerosol/Small Package	Tunnel Occupants and Surrounding Population
C/B/R	Foot	Surface Access Road to Tunnel Vent Intakes	Vial/Aerosol/Small Package	Tunnel Occupants and Surrounding Population
C/B/R	Vehicle	Tunnel Air Supply System	Vial/Aerosol/Small Package	Tunnel Occupants and Surrounding Population
C/B/R	Vehicle	Tunnel Roadway	Vial/Aerosol/Small Package	Tunnel Occupants and Surrounding Population
C/B/R	Vehicle	Surface Access Road to Tunnel Vent Intakes	Vial/Aerosol/Large Package on Truck	Tunnel Occupants and Surrounding Population
C/B/R	Vehicle	Surface Access Road to Tunnel Vent Intakes	Vial/Aerosol/Large Package	Tunnel Occupants and Surrounding Population
C/B/R	On Foot in Transit Car	Tunnel Roadway	Vial/Aerosol/Large Package	Tunnel Occupants and Surrounding Population
C/B/R	Transit Car	Tunnel Trainway	Vial/Aerosol/Large Package on Train	Tunnel Occupants and Surrounding Population
Hazardous Materials	Vehicle	Tunnel Roadway	Truck	Any Place in Tunnel
Hazardous Materials	Transit Car	Tunnel Trainway	Device on Train	Any Place in Tunnel
Cyber Attack	Digital	Virtual	Virus Code	C&C
Maritime Incident (Anchor Drag)	Ship	Water Above Tunnel	Passing Ship	Tunnel Shell

C&C = command & control.
IEDs = improvised explosive devices.
MEC = mechanical, electrical, and communications.

within the structure and surrounding areas. Fire and smoke will decrease visibility to unsafe levels, precipitate collision of vehicles and equipment, and cause personal injury. A fire controlled by firefighting may still result in smoke and water damage at a level sufficient to render a tunnel unfit for use or occupancy. The related assets are the following:

- **Tunnel structures.** A fire may cause damage to the integrity of a structure and its engineered support bracing. The heat of a flame may distort all standard tunnel materials sufficient to require closure for repair. The damaging effects of a fire are consistent across bored, cut-and-cover, and immersed tube tunnel construction.
- **Portals.** Smoke and flame damage may threaten engineered works to weaken a portal. Damage or destruction may also be inflicted on monitoring equipment situated at the portal to a tunnel such as over height detection units, heat sensors, carbon monoxide detectors, and closed-circuit camera units.
- **Vent shafts.** Fire, heat, and water damage may affect air intake and exhaust towers, machinery, and required air filtering equipment. The damage would require replacement.
- **Stations (passenger tunnels only).** A fire may damage or destroy wood, metal, and masonry structures that are necessary for normal human occupancy. Certificates of occupancy are routinely revoked when a fire causes damage to a structure. A small conflagration, with flame and smoke, may render a station unfit for occupancy and disallow its use by persons, vehicles, and equipment; it will be unfit until environmental abatement is complete and repairs are made to meet regulatory code. A station unfit for occupancy eliminates its primary function within the system, which is the transfer of passengers to railcar.
- **Distribution channels.** The destructive path of flame and smoke may melt sheathing, iron piping, polyvinyl chloride (PVC), and metal conduit, thereby damaging the contents beyond repair. Pipes carrying water could serve as conduits for burning oil. Water used in firefighting efforts may have a destructive effect on power and communication lines. The loss of a utility in or near the tunnel structure will deny service to the surrounding areas, including any businesses, homes, or schools. Utilities may also facilitate the flow of water and other materials along their pathways and in entry and exit locations.
- **Control centers.** Flame and smoke may destroy the physical structure and all mechanical equipment of a control center and endanger the lives of personnel assigned to that facility. Water damage to equipment and structure may also occur in firefighting efforts. The loss of a control center would severely affect the ability of a transportation system to operate. The impact would be particularly severe on rail systems that rely on remote monitoring and sensors to control movement.
- **Substations.** Fire may damage or destroy the physical structures containing utility equipment and connections. A fire may also sever the power feed and monitoring systems of a substation, thereby rendering the station unfit for use. Equipment rendered unusable by the effects of a fire will need to be replaced prior to the operation of a tunnel to maintain the ability to evacuate water and provide power. Substations may also be adversely impacted by firefighting techniques that may send soiled water and debris into the plenums, thereby jamming lines and pump rotors.
- **Utility building.** Fire may damage the utility terminus structures, rendering them unusable.

Structural Integrity Loss by Natural Causes

Despite the best efforts of engineering and maintenance, the potential danger of structural integrity loss to tunnels and supporting infrastructure from unforeseen circumstances will always exist. There is no known method to guarantee that a structure will never fail or deteriorate. Proper design, construction, and maintenance may drastically reduce the likelihood of a sudden failure. However, unseen geotechnical or aquatic forces may go undetected by asset owners. Inconsistencies and lapses in the design, construction, and maintenance of a tunnel may collude to create the conditions for a sudden structural integrity loss.

Structural integrity loss may be sudden or slow acting. The scope of this damage may be minimal, such as a crack in the wall requiring remediation or a pavement ripple requiring the temporary relocation of traffic. Integrity loss may also be catastrophic, resulting in total collapse or flooding of a structure, wreaking widespread loss of assets, and loss of life. The related assets are the following:

- **Tunnel structures.** Loss of structural integrity threatens to collapse the bore, tube, or constructed below-grade area wholly or partially. A whole or partial collapse will force the closure of the asset for an undetermined amount of time. Minor integrity losses also drastically increase the opportunity for water inflow, thereby inducing a progressive loss of material strength. Loss of integrity directly affecting a rail bed or track may unsettle the transit area of the tube. Disturbances to only the transited area will slow road traffic until repair; these disturbances will likely halt rail traffic because of the deflection of the rail.
- **Portals.** Portal construction is subject to the same stresses as the tube areas. Whole or partial collapse will force a closure of the transit areas and nearby access paths.
- **Vent shafts.** Loss of structural integrity may destroy air intake and exhaust plenums, shafts, and towers. A shift in the support of a vent shaft area can alter the load-bearing capability to support heavy machinery necessary for air

purification. The absence of fresh air delivery into the below-grade structure can detrimentally impact that facility's ability to support life and safety.

- **Stations (passenger tunnels only).** A passenger station may be made partly or wholly unsafe by a structural integrity loss. Falling debris, unsettled steps and walkways, and uneven road or rail surface contribute to an unsafe environment.
- **Substation.** A substation may be disturbed or made nonfunctional by a loss of structural integrity. Machinery or piping may be made uneven, thereby interrupting the designed flow of the station. Power brought in by hard wire may be interrupted by the movement or decay of the structures on which they are tethered.
- **Control centers.** Control centers lose functionality when a loss of structural integrity occurs in a tunnel system. Sensors, cameras, alarms, radio signals, and detectors are normally hard wired inside a tunnel system and tethered to a wall, shaft, plenum, or stairway system. The partial collapse of a support for one of these remote communication systems would disable the unit and eliminate its use to a control center.
- **Distribution channels.** Similar to the operation of a control and detection system, distribution channels would be interrupted or impaired by the whole or partial loss of the structures that they monitor or are attached to. Buried utilities, located within the footprint of the tunnel structure or in nearby corridors, may be affected by the geotechnical alteration subsequent to a whole or partial collapse. Utilities connected by piping or hard wire may be severed or cracked. The collapse may allow water to intrude on soft wire networks such as fiber optic to corrode connectors. Power utilities may also experience water intrusion that may result in surges, overloads, and possibility of electrocution.

Introduction of Hazardous Materials

A tunnel system may be threatened by the accidental discharge of hazardous materials into the confined space of the tunnels or the stations. Hazardous materials can take a liquid, solid, or gaseous form. Even minimal quantities of some materials can cause serious injury to tunnel system users. Hazardous materials can range from common industrial cleaners used by tunnel workers to a canister of pepper spray set off by a commuter. In both circumstances, it is unlikely that the maintenance worker or the commuter entered the tunnel system with the intent of discharging hazardous material into the air. Materials may also include hazardous liquid, debris, or waste product moved into the tunnel system by a vehicle, truck, or rail car.

Public vehicular tunnel systems may forbid the transport of dangerous materials through below-grade areas, but these injunctions alone cannot stop private vehicles and trucks from attempting to transport them. Hazardous materials will enter the tunnel systems in varying quantities, and many will exit the system without incident or release. Through driver error or unfortunate circumstance, hazardous materials may leak or be released into the tunnel. Many hazardous materials require specialized remediation that will close a road or transit tunnel to allow processing. The related assets are as follows:

- **Tunnel system and structure.** The introduction of hazardous materials into a tunnel system constitutes a hazard to the safe use of the tunnel and requires immediate remediation. When a material is identified as potential or actual hazardous material, the area containing the hazard must be taken out of service for remediation. This closure adversely affects the use of the tunnel system and disrupts traffic flow. The tunnel as a system is adversely disrupted. The structural integrity of the tunnel may also be damaged by the introduction of certain hazardous materials, thereby requiring heavy repair under closed conditions.
- **Portals.** Hazardous material introduction may have the same adverse impacts to a portal as to the tunnel structure. Certain hazardous materials require remediation, and remediation may require full or partial closure of the road or rail line. Closures will affect flow through the portals.
- **Stations (passenger tunnels only).** The introduction of hazardous materials may constitute an immediate safety hazard and require the partial or full evacuation of the station to commence remediation efforts. Any evacuation would be an adverse impact.

2.3.2 Threat Scenarios in Relation to Assets

Introduction of Small IEDs

Explosives are materials capable of violent decomposition, which often takes the form of extremely rapid oxidation (i.e., burning). Explosions are the result of sudden and violent release of gas during the decomposition of explosive substances.

Small IEDs are defined as explosive or incendiary production materials or devices small enough to be easily concealed. Compact or small devices are easily concealed among a person or personal belongings and may only be detected by deliberate use of equipment, processes, or close observation. The destructive pattern of any explosive device has the potential to damage every object within its blast radius. A small conventional explosive has the capacity to kill or injure anyone within its blast radius. The related assets are as follows:

- **Tunnel structures.** A hand-carried IED will damage the portion of the tunnel located within the blast radius. The portion of the structure damaged may be relatively small or extensive. The hand-carried IED will cause the temporary closure of the tunnel for evacuation and repair.

- **Portals.** Similar to the tunnel structure, the portal may be damaged if it is within the blast radius of the hand-carried IED. The portal will be closed temporarily for repair.
- **Vent shafts.** Similar to the tunnel structure, the vent shaft may be damaged if it is within the blast radius of the hand-carried IED. The shaft or intake structure will be closed temporarily for repair.
- **Stations (passenger tunnels only).** A hand-carried IED set to detonate in a passenger station will likely cause more damage to persons than to property. A device set to explode in a passenger station will have been intended to harm or frighten people. The relative space difference between a station and a tunnel will allow a greater physical area to absorb the blast, thereby lessening the physical damage to the station. A mass casualty incident will likely lead to the closure of the station for an extended period, but not permanently.
- **Substation.** Similar to the tunnel structure, the system's substation may be damaged if it is within the blast radius of a hand-carried IED. The substation will be closed temporarily for repair.
- **Control centers.** Depending on the placement of an explosive device, the blast may throw the facility off line or threaten the facility's ability to safely hold persons and equipment. A control center located many miles from the scene of an explosion may be physically unaffected but still see a loss in monitoring capacity to the affected area. A control center located at the site of an explosive blast may be directly affected, evacuated, and possibly destroyed.
- **Distribution channels.** A small blast will damage or destroy wiring, piping, or vents located within the blast zone. Loss of these distribution channels may force the closure of the tunnel system for repair.
- **Utility terminus building.** A building may be partially closed for repair as the result of the successful delivery of a small IED. Loss of a utility may have a cascading effect on downstream systems, thereby debilitating service in the tunnel system.

Introduction of Medium-Sized and Large IEDs

Medium-sized and large explosives typically rely on a mobile delivery system, such as a car, truck, or rocket, or are stealthily placed in a chosen area prior to detonation. The power of a medium-sized or large explosive is wholly destructive to persons and property. In the confined atmosphere of a tunnel system, the force of a blast will be absorbed by the components of the tunnel system, causing casualties and destruction. Large quantities of explosives require efforts at interdiction prior to their placement or delivery. Vehicle-borne delivery systems are noticeable to defenders. The related assets are as follows:

- **Tunnel structures.** A vehicle-borne explosive will damage a significant portion of the tunnel located within the blast radius. The vehicle-borne explosive will cause a long-term closure of the tunnel for evacuation and repair. A well-placed large explosive may cause the tunnel structure to collapse and require rebuilding. A large explosive may also cause a mass casualty incident.
- **Portals.** Similar to the tunnel structure, the portal may be damaged or destroyed if it is within the blast radius of the vehicle-borne explosive.
- **Vent shafts.** Similar to the tunnel structure, the vent shaft may be damaged or destroyed if it is within the blast radius of the vehicle-borne explosive. The shaft or intake structure may require reconstruction.
- **Stations (passenger tunnels only).** A vehicle-borne explosive set to detonate in a passenger station will cause significant damage to persons and property. A mass casualty incident will likely lead to the closure of the station for an extended period, if not permanently. Reconstruction of the station will need to occur.
- **Substation.** Similar to the tunnel structure, the substation may be damaged or destroyed if it is within the blast radius of a vehicle-borne explosive. A substation will require reconstruction if the damage is significant.
- **Control centers.** Depending on the placement of a vehicle-borne explosive, the blast may throw the facility off line or threaten its ability to safely hold persons and equipment. A control center located many miles from the scene of an explosion may be physically unaffected but still see a loss in monitoring capacity to the affected area. A control center located at the site of an explosive blast may be directly affected, evacuated, or possibly destroyed.
- **Distribution channels.** Any explosive blast will damage or destroy life safety and monitoring systems located within the blast zone. Interconnected distribution channels will be severed, thereby limiting or destroying their usefulness to another part of the tunnel system not directly affected by the blast. Systems will need to be reconstructed.
- **Utility building.** Utility lines and connectors may be damaged or destroyed if they are within the blast zone. Loss of a utility will have a cascading effect on downstream systems, debilitating service in the tunnel system and adjoining areas.

Introduction of Chemical Agents

According to the Federal Emergency Management Agency (FEMA), as promulgated in *Emergency Response to Terrorism Job Aid* (which is available online at http://www.usfa.dhs.

gov/downloads/pdf/publications/ert-ja.pdf), there are five classes of chemical agents, all of which produce incapacitation, serious injury, or death:

- **Nerve agents** damage the nervous system of a person and are extremely effective in small doses. Exposure is achieved through the respiratory tract and the skin. Nerve agents are deadly and fast acting, and symptoms include difficulty breathing, seizures, headaches, and salivation. All nerve agents require handling and treatment with extreme care. Well-known nerve agents include sarin (GB), soman (GD), tabun (GA), and V agent (VX).
- **Blister agents,** also known as vesicants, include phosgene and mustard gas. Vesicants are absorbed through the eyes, skin, and lungs. They attack tissue and cause severe blistering. They may lead to seizures, blindness, and pulmonary edema. Blister agents are treatable and were first introduced during World War I.
- **Blood agents** quickly diminish the ability of the body to absorb oxygen into the bloodstream, thereby depriving the organs of oxygen. Common types of blood agents include hydrogen cyanide and arsine, both of which are used in industrial applications. Blood agents enter the body through the skin or the respiratory tract and provoke cherry red lip color convulsions, nausea, and respiratory arrest. Affliction by a blood agent is treatable.
- **Choking agents** interfere with the breathing process and, if left untreated, may induce asphyxiation. Choking agents include common compounds such as chlorine, ammonia, hydrogen chloride, and phosphorous. Common symptoms include coughing; shortness of breath; and a burning sensation in the eyes, nose, and throat. There are no known antidotes to choking agents, but successful medical treatment is available.
- **Irritant agents** are agents designed to temporarily incapacitate a person. They generally do not have long-term effects or induce death. Common irritants include pepper spray, mace, and tear gas, all of which will induce tearing eyes, coughing, and throat irritation. These effects are temporary and treatable.

The agents' means of affliction and effects are outlined in *Emergency Response to Terrorism Job Aid* and in the succinct Department of Health and Human Services's *Terrorism and Other Public Health Emergencies: A Reference Guide for Media* (which is available online at http://www.hhs.gov/emergency/mediaguide/PDF/00.pdf).

The related assets are as follows:

- **Vent shafts.** Similar to a biological agent, air intake facilities may be the point of introduction for a chemical agent. By introducing a chemical agent into a vent shaft, an aggressor would be able to introduce the agent into the ventilation system. This method may also dilute the concentration of the chemical agent. An affected vent shaft would need to be quarantined, decontaminated, and likely decommissioned due to damage, public fear, or use as evidence in a criminal investigation.
- **Stations (passenger tunnels only).** Stations would be the likely scene of both introduction of the chemical agent and the mass casualty. The means to introduce a chemical agent into a station is relatively unsophisticated. An aggressor could enter the station with a vial, bag, or other carrier and open it on the platform, thereby exposing the tunnel users to the chemical agent. The station would be designated as out of service; it would become a mass casualty treatment area, crime scene, and site of an infected structure requiring decontamination. Upon decontamination and release as a crime scene, partial or full reconstruction may be necessary.

Introduction of Biological Agents

The introduction of a harmful biological agent into a tunnel transportation system is a threat of high damage potential and low probability. There is little historical data on the use of biological agents in the United States as a threat against tunnel transportation systems.

Biological agents are weaponized versions of organisms that occur in the natural environment. Bacteria, viruses, and toxins can be manipulated to cause widespread contagion and infection among a targeted population. Biological agents can be released into the air of a tunnel system and provoke either an immediate or delayed response from the affected individuals.

Biological agents are very difficult to manufacture, handle, and deliver. Their effectiveness is impacted by wind, moisture, and air removal systems. Well-known biological agents include botulism, smallpox, and anthrax. Symptoms of a biological agent vary, but may include increasing fatigue or flu-like symptoms. Victims may suffer localized paralysis, swelling, rashes, or fever. Treatment is possible for many, but not all, biological agents.

Introduction of a biological agent into a transportation tunnel would likely cause a delayed medical treatment situation. Travelers would begin seeking medical treatment hours or days after the exposure. Damage to the tunnel infrastructure would be contained to directly affected equipment and areas, all of which would require complete decontamination. During the period of decontamination, all equipment must be quarantined and replaced.

The related assets are as follows:

- **Vent shafts.** Air intake facilities may be the point of introduction for a biological agent. By introducing a biological agent into the air shaft, an aggressor would be able to introduce the agent into the ventilation system. This method may also dilute the concentration of the biological agent. For a persistent agent, an affected vent shaft would need to be quarantined, decontaminated, and likely decommissioned due to damage, public fear, or use as evidence in a criminal investigation.

- **Stations (passenger tunnels only).** Stations would be the likely scene of both the introduction of the biological agent and the mass casualty incident. The means to introduce an agent into a station is relatively unsophisticated. An aggressor could enter the station with a vial, bag, or other carrier and open it on the platform, thereby exposing the tunnel users to the biological agent. Once identified as contaminated, the station would be designated out of service; depending on the speed of onset of symptoms, it could become a mass casualty treatment area, crime scene, and infected structure site requiring decontamination. Upon decontamination and release as a crime scene, partial or full reconstruction may be necessary.

Introduction of Radiological Agents

A radiological attack would have a destructive impact on a tunnel transportation system, nearby environments, and the user community. Radiological contamination disrupts the cell structure of a victim, causing sickness and death. A victim may experience delayed symptoms and may mistake the cause of the symptoms for a flu-like illness. Radiological material is difficult to manufacture, handle, and deliver. It can be as deadly to the attacker as to the victims.

Facilities and equipment would both be placed out of service and possibly abandoned. Extensive decontamination efforts would be required to restore them to use. The related assets are as follows:

- **Tunnel structure.** A successful radiological attack would adversely affect the tunnel structure. Damage may be immediate (resulting from the explosive used in the delivery) or long term (resulting from the contamination of the structure with radiological material). Immediate blast damage may affect the integrity of the structure, including supports, braces, and engineered works that withstand water intrusion. The long-term effects of radiological contamination might require lengthy remediation, including replacement of sections or construction of alternative routes. These scenarios would require a long-term closure of that area of the system or abandonment.
- **Portal.** The portal would be similarly impacted as the tunnel structure. Depending on the placement of the explosive delivery device, the portal may become unsteady and contaminated. Damage may require reconstruction, long-term closure, or abandonment. The effect of a radiological threat successfully executed on an occupied passenger station would be a mass casualty event and would lead to closure of the station for an extended period for abatement and reconstruction. Severe contamination or severe damage from the explosive delivery could result in abandonment. The impact to the system could be drastic. The station might not be used as a transit way, entry point, or egress point for a considerable amount of time.

A NOTE ABOUT BIOLOGICAL, CHEMICAL, AND RADIOLOGICAL ATTACKS: Biological, chemical, and radiological attacks may not be readily apparent at the site of introduction within the tunnel system. The introduction of these agents may be discernable only later, when victims seek medical treatment and the origin of their problems are traced to the use of a common tunnel. The effect of an attack would remain consistent with the descriptions provided, yet the discovery of the attack would be different than other primary hazards and threats described. An extended discussion of chemical, biological, and radiological agents and transportation system response options is presented in *NCHRP Report 525, Vol. 10: A Guide to Transportation's Role in Public Health Disasters*.

Cyber Attack

Closed-circuit television (CCTV), air quality testing, and traffic algorithms are commonplace to ensure the smooth, safe use of a tunnel. The deployment of a concerted effort to deny the use of digital technology to the tunnel operator is a threat. The venue to attack the computer network of a tunnel operator is remote and virtual. The introduction of a virus into a remote network is commonplace in today's environment. Minimal technology is needed to launch a cyber attack. The related asset is as follows:

- **Control centers.** Technology is crucial to the monitoring and safe operation of a tunnel. Control centers remotely view, test, and monitor a tunnel environment using digital transmission and other technology.

Maritime Incident

The occurrence of a maritime incident, specifically a ship sinking over a subaqueous tunnel or dropping a depth charge on the tunnel, is a threat to the safe operation of a water tunnel. Subaqueous tunnels located under navigable waterways are potentially at risk. A maritime incident may result from a navigational error or mechanical defect aboard the ship. A maritime incident may also result from an intentional act by an aggressor.

An intentional maritime incident may be part of a more elaborate attack designed to simultaneously inflict damage on multiple assets. For example, the use of a sunken vessel to damage the tunnel shell will cause a great amount of first responder resources to be devoted to mitigating the waterborne disaster. An aggressor may take advantage of the concentration of resources at that site and strike another area deemed to be the higher-value target. In this example, the sunken vessel only serves as a delivery mode for an explosive to reach the tunnel shell. A quantity of explosives detonating outside the shell would damage the shell. The extent of damage will be determined by the exact placement of the explosive and the quantity deployed. All explosions occurring from the outside on the tunnel shell will cause the closure of the tunnel to users for a period of time while the damage is inspected and mitigated. Efforts will also be expended to evacuate any tunnel users in harm's way.

The related asset is as follows:

- **Tunnel structures.** Subaqueous tunnels may suffer damage or collapse if struck by a ship of sufficient size. The damage or collapse may allow sufficient water inflow to flood the tunnel, thereby endangering lives, property, and the use of the tunnel.

Fire (Arson)

Arson is the criminal act of enacting a conflagration on property. The act is intended to inflict injury to persons and damage to property. Arson that is intended to damage or destroy property may also recklessly endanger the safety of tunnel users and first responders. An occurrence of arson could inhibit the ability of the tunnel operator to open the tunnel for a period of time. A 341 million British thermal units (MBTU) per hour (100 MW) fire is the maximum design fire currently used globally for most road tunnels and is the maximum size fire that can be controlled by the majority of road tunnel ventilation systems. In typical transit and rail tunnels, the maximum design fire size is much lower, in the neighborhood of 68.2 to 170.5 MBTU per hour (20 to 50 MW). Any fire larger than 341 MBTU per hour (100 MW) will not be controllable in any tunnel and, therefore, could be a major catastrophic event. Therefore, this project considered only fires larger than 341 MBTU per hour (100 MW).

Sabotage of MEC Systems

A premeditated, intentional disruption of tunnel MEC systems presents a threat to all nearby below-grade tunnel structures. Loss of system function may alter the effectiveness of safety and operational systems, thereby presenting a tunnel condition unfit for general use. Systems designed for the evacuation of water, delivery of power, provision of fresh air, or monitoring of traffic may be made unusable for an extended period. Replacement of the sabotaged system may incur great costs and lengthy installation times. Significant loss of MEC systems may cause tunnel operations to be suspended. The related assets are as follows:

- **Tunnel structures.** A disrupted utility may cause the suspension of tunnel system operations due to unsafe conditions. Power loss in a tunnel system will likely trigger a closure of the underground area and evacuation of standing populations. Water or sewer inflow will trigger an immediate suspension of tunnel operations or severe restrictions on travel through the system.
- **Vent shafts.** Exhaust and air intake machinery may suffer a loss of function due to a loss of power or a sudden water inflow.
- **Stations (passenger tunnels only).** Sabotage of MEC systems may adversely impact a passenger station due to power loss, which cripples lighting, ventilation, and safety systems. Disrupted sewer, steam, and water lines allowing material to enter the station could create an unsanitary condition, thereby precipitating injury and evacuation.
- **Substation.** Facilities containing connections for pumps and feeder machinery may suffer a loss of function due to a loss of power.
- **Control Centers.** Monitoring capabilities of a control center are diminished or negated by a loss of power. Staffed control centers are also subject to evacuation because of unsafe or unsanitary conditions that may be found with a disrupted water, steam, or sewer pipe.
- **Distribution channels.** Piping, wiring, conduit, and shafts to control fire control, ventilation, smoke detection, carbon sensor, and video monitoring equipment may suffer a function loss due to a power loss or intentional damage.
- **Utility terminus building.** This facility may be the direct target of an aggressor determined to damage or interrupt MEC systems within a tunnel system. Loss of the utility terminus building would require intensive repair efforts.

2.4 Conclusions

To varying degrees, the hazards and threats presented in this chapter have occurred in the United States. They will likely present themselves again. Their capacity to close a tunnel system, however briefly, is proven. Although their detrimental effects on the tunnel system, equipment, and users may be mitigated, the more consequential security threats may have unprecedented consequences in terms of major tunnel damage and indeterminate service impacts.

CHAPTER 3

Case Studies

3.1 Introduction

This chapter consists of case studies of a variety of tunnel incidents that occurred between 1979 and 2004. Each case study includes a list of references.

After an incident similar to the incidents described herein, it is common practice for in-house or outside investigatory or oversight agencies to report on the incident. However, such reports are often unpublished and are rarely available to general readers. The information contained in these case studies came from published sources that were readily available in libraries or through the Internet, without any special access to the systems described. Although some published oversight reports were reviewed and included in the list of additional sources at the end of this report, most of the case study information presented herein came from newspaper accounts and after-incident analyses in magazines and academic journals. Because such sources can contain erroneous information, a piece of information was typically discounted if it differed radically from that found in the majority of other accounts. However, there may be facts or interpretations of facts that cannot be gleaned solely from published sources.

The case studies were selected for their applicability to the overall project. They represent sketches of a wide variety of types of emergencies. The incidents include willful acts of arson and bombings in transit systems, road and rail accidents in tunnels, fires in tunnels and transit stations, and an urban tunnel flood. Summaries, pre-incident and incident analyses, fatalities and injuries, fire and emergency response (including, in some instances, police response), damage and service restoration, and findings of the agencies involved in the incidents and various oversight groups are presented. Each case study ends with a list of references pertaining to it.

The chapter concludes with Table 4, which briefly summarizes each incident; a discussion of issues raised by the incidents; and Table 5, which shows the role of MEC systems in the case studies.

3.2 Case Study Descriptions

3.2.1 Moscow Subway Suicide Bombing

Location:	Moscow, Russia
Date:	February 6, 2004
Incident Category:	terrorist bombing
Tunnel Length:	N/A; subway train
Fatalities and Injuries:	39 fatalities, 100+ injured

Synopsis

A bomb, later linked to Chechen separatists, exploded inside a crowded Moscow subway train during the morning rush hour. The bomb destroyed the second car of the train as it left the Avtozavodskaya station in southeast Moscow while traveling toward the center of the city. The incident was one of three subway-related bombings attributed to Chechens.

Analysis of Pre-Incident Information and Events

The Moscow subway system, which carries an average of 8.6 million riders a day, is considered the world's busiest subway system. The February 6, 2004, blast was neither the first nor the last subway-related bombing, although it was the deadliest up to that time. A bombing in a subway car in June 1996 killed four people; a bomb blast on August 8, 2000, ripped through a Moscow underpass leading from an underground railway station at central Pushkin Square, killing 13 people and injuring at least 90; another bomb had injured about a dozen people in February 2001. The incidents were blamed on Chechen rebels, although the Pushkin Square bombing, according to police, may actually have been a turf battle between either rival businesspeople or criminal gangs. Regardless of motives, the bombings led to increased surveillance of riders, particularly those who appeared to be Chechens from the North Caucasus area, but the level of crowding in the system makes programmed or thorough surveillance impossible. In addition to police routinely stopping those who appear suspicious, there are security cameras throughout the system.

Analysis of the Incident

A bomb exploded at 8:45 a.m. in a crowded rush-hour Moscow subway train on the Zamoskvoretskaya Line (the Green Line), killing at least 30 people and wounding more than 130 passengers. The bomb, which was hidden in a backpack, exploded in the second car of the train as it left the Avtozavodskaya station traveling toward the center of the city. The train had moved 984 feet (300 meters) out of the station when the explosion occurred near the first door of the second car. The explosion shattered the train's windows, welded metal seats to the train, and hurled bodies and body parts out of the train. The third car was also damaged, and the blast shattered windows in other cars. The train traveled several hundred feet before coming to a stop.

Train operators initially had problems opening the car doors. Reports as to how the doors were opened differed; some survivors said that the operator was able to open the doors, but some survivors maintained that the passengers pried the doors open. Once the doors were opened, some survivors walked approximately 2 kilometers (1.2 miles) through the subway tunnel to the Paveletskaya station. Their walk took them under the Moscow River and closer to the Kremlin. At the Paveletskaya station, they were met by ambulances and firefighters.

Fatalities and Injuries

The fatalities and injuries all occurred on the train. Thirty-nine people were killed immediately in the blast. Of the approximately 135 passengers injured, the vast majority (estimates ranged from 113 to 122) required hospitalization.

Fire and Emergency Response

Firefighters, police, and emergency medical personnel responded to the incident in one of Moscow's deepest underground stations. Bodies and body parts were scattered along the tracks, and many bodies remained in the train, covered in blood and soot. More than 700 people were evacuated from the two stations, many transported from the scene by buses that were rerouted to assist in the evacuation to prevent further clogging of area streets. Police officers barricaded the streets nearest the two stations and stopped all train traffic on the subway line. Because of the reliance on public transportation by commuters, street-level traffic congestion was considerable.

Wounded passengers were brought up on stretchers on long escalators to the more than 50 ambulances that gathered outside the Avtozavodskaya station. Other ambulances gathered at the Paveletskaya station entrance, from which many of the survivors who were able to walk were evacuated. Some survivors were aided by police officers who were riding in the train two or three cars behind where the bomb went off.

Damage and Service Restoration

Both subway stations were reopened soon after the bombing. The Avtozavodskaya station was almost immediately turned into an impromptu memorial, with people laying flowers on the station platform.

Fear of additional explosions brought intensified security at subway and rail stations, airports, and other public places. One other subway station (Tekstilshchili), not far from the Avtozavodskaya explosion, was evacuated for part of a non-rush-hour Saturday afternoon and evening after an anonymous threat was called in by telephone.

Conclusions

The explosion was attributed to Chechen separatists who may have been attempting to influence the presidential election that took place on March 14, in which President Putin was reelected. The incident was the 13th terrorist attack of the year in Russia. The terrorist attacks were mostly suicide bombings and resulted in more than 260 people being killed. More than 60 of the deaths were in Moscow. Two previous bombings were in either a tunnel or subway station, including the August 8, 2000, bombing in a pedestrian tunnel near Pushkin Square, in which 13 people were killed and at least 90 injured, and the February 5, 2001, bombing of the Belorusskaya subway station, in which there were no fatalities but nine people were injured.

The incident resulted, as had the others, in enhanced security at public transportation facilities in Moscow and other major Russian cities. However, government officials reported there was little they could do to prevent bombings as long as the perpetrators were prepared to die along with those killed in the attacks. The problem in preventing such bombings was compounded by the conflicting reports as to whether the bomb was planted or carried. The conflicts stemmed from some investigators having viewed a videotape of what they believed were the suspected bomber and her alleged accomplice standing on the platform of the station before boarding the train. Others believed the explosion was caused by an unattended bag left in the car.

The difficulty of preventing a suicide attack in a subway station was reinforced a few months later. On August 31, a female suicide bomber set off a bomb outside a Moscow subway station, killing at least 10 people and injuring more than 50 others. The bomb exploded at about 8:15 p.m. near the Rizhskaya station in northeast Moscow, located near one of the city's major thoroughfares. Although it was after rush hour, the subway and surrounding area were busy because it was the last day of summer vacation and many people were returning home. Many subway passengers were also returning to their homes from the center of Moscow, thereby contributing to crowds at the station and in the area.

The explosion did not affect the subway directly, but two parked cars in the area were set on fire and passersby were injured by the metal fragments, the smoke, and shattered glass from shop windows. The explosive used in the bombing was Hexogen, which was the same explosive that had been used on August 24, 2004, to explode Russian civilian aircraft on domestic flights that originated in Moscow.

It was not determined whether the bomber had intended to detonate herself inside the subway, but there were reports that she had been walking toward the station and turned around when she saw two police officers near the entrance checking documents and searching bags. Instead, she set herself aflame in an area between the subway station and the Krestovsky department store and supermarket complex nearby. Lending credence to the view that the subway station had been her target, the 29-year-old Chechen woman who set the explosion was the sister of the woman suspected of detonating the blast on one of the two planes that were blown up on August 24, 2004.

The large number of bombings resulted in problems for Moscow's hospitals, which have become trauma centers on a continuing basis.

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3.2.2 Jungangno (Chungang-Ro) Subway Station Arson Fire

Location:	Daegu, Korea
Date:	February 18, 2003
Incident Category:	arson fire
Tunnel Length:	N/A; subway system station
Fatalities and Injuries:	198 fatalities, 147 injuries, 50+ missing

Note: Jungangno and Daegu are the preferred English spellings of the station and city name as translated by the City of Daegu and the Daegu Metropolitan Subway System.

Synopsis

At about 10 a.m. on February 18, 2003, a mentally unstable subway passenger trying to commit suicide threw flammable liquid inside a car of a Daegu, Korea, subway train that was carrying 600 people. Although passengers tried to stop the arsonist from lighting the liquid with a cigarette lighter, ignition occurred as the train pulled into the underground Jungangno station, four levels beneath Daegu's central city. The arsonist escaped through the closing doors just as the train burst into flames. The fire was fueled by flammable seats and other interior car furnishings. The system's control center allowed another six-car train traveling in the opposite direction to enter the tunnel moments after the first train burst into flames. The doors of the second train locked shut when its driver stopped the train in the tunnel and removed the master controller key, trapping passengers inside as the train cars filled with smoke and noxious fumes from the burning train.

Analysis of Pre-Incident Information and Events

Daegu is Korea's third largest city and has 2.5 million residents. It is a textile center in the south of the Korean Peninsula, about 200 miles (322 kilometers) southeast of Seoul. Construction of the 16-mile (25.7-kilometer), 30-station

Line 1 of the Metropolitan Subway began in 1992 and was inaugurated in two stages in 1997 and 1998. It was extended toward the southwest in 2002. The Jincheon-to-Jungangno segment opened to passengers November 26, 1997. The Jungangno-to-Ansim segment opened on May 2, 1998, and the 2,300-foot (700-meter) Jincheon-to-Daegok segment opened on May 10, 2002. Hanjin Heavy Industry manufactured the subway cars.

While the Daegu Metropolitan Subway prided itself on its incorporation of the latest in safety technology when it began construction, the Jungangno fire was one of five major incidents associated with the line since construction commenced in 1992. In January 1994, supporting equipment at a subway construction site collapsed, leaving one man injured. A gas explosion near another subway construction site injured 143 and killed 101 bystanders (including eight schoolboys) in April 1995; it was deemed the worst subway accident in the nation's history. Because of that accident, the Daegu government suspended construction of the system's Line 2 for several weeks. Another explosion in August 1995 resulted in four casualties. In January 2000, a subway section under construction collapsed, killing three people and closing part of the city's main road. In January 2002, a bus passing an intersection near a subway construction site killed and/or injured four people. The station where the arson occurred had passed a safety check approximately 5 months prior to the incident.

Analysis of the Incident

The incident began at 9:55 a.m. on February 18, 2003, on the fourth car of the six-car Train 1079 at the underground Jungangno station, four levels beneath the city. A 56-year-old man with a history of depression, Kim Dae Han, removed a plastic milk carton containing a flammable substance, most likely gasoline, from a black bag and attempted to light it with a cigarette lighter. As subway passengers tried to stop Han from flicking the lighter, some of the liquid spilled onto the floor of the car. Just as the car doors were closing for departure, the lighter ignited and the car caught fire. Han escaped through the closing doors and was seized by passengers, but the fire spread rapidly and black smoke rose. An ensuing power failure locked the doors, leaving passengers trapped in the burning car as well as in the five other cars in the subway consist.

The first reports of the fire were apparently generated within seconds of the doors closing on the burning car via cell phone calls from distraught passengers calling loved ones; however, official communication channels were not opened until at least 10 minutes had lapsed. Because of this communication gap, a six-car train (1080) traveling in the opposite direction entered the tunnel moments after the first train burst into flames. The driver of the second train had questioned train control as to whether he should enter the station, saying, "It's a mess. It's stifling. Take some measures please. Should I evacuate the passengers? What should I do?" The control center only advised the driver to drive carefully as he entered Jungangno station, since there was a fire. The driver approached the station, stopped the train in the tunnel, exited the cab, and removed the master controller key. This locked the doors shut, trapping passengers inside the train as its cars filled with smoke and noxious fumes.

The fast-moving fire was fueled by the train's seats and other interior products that were not fireproofed. This was, in part, because national safety standards for train interiors were not introduced until 1998, 1 year after revenue service began in Daegu. Prior to this date, Hanjin Heavy Industry used fire-retardant materials only in cars made for export.

Fatalities and Injuries

In August 2003, Daegu officials confirmed that 198 people had died in the fire, at least 147 were injured, and approximately 50 people were unaccounted for.

Fire and Emergency Response

In an eerie echo of the September 11, 2001, terrorist attacks in the United States, families reported receiving cell phone calls from loved ones trapped in the incident before officials were aware of it. This had also occurred during the Tauern Tunnel fire in Austria in 1999, when a truck loaded with paint collided with an oncoming car and many of those who were trapped used cell phones to contact those outside. In Daegu, emergency communications within the subway system did not register for more than 10 minutes after the incident began. This not only delayed emergency response but also led to the second train being permitted to proceed directly into the fire.

In addition to the communication failures, the subway's electrical systems also failed. This led to an absence of emergency lighting, the shut-down of the ventilation systems, and the inadequacy of any existing emergency evacuation procedures. Access to the station was also hampered because it is four levels below grade, with three levels of stairs between the platform and the surface.

All subway traffic was halted and officials also cut all power, fearing that the overhead cables would collapse and electrocute people. Because of the absence of emergency lighting and ventilation, firefighters from the more than 60 fire vehicles that responded to the scene were met with thick smoke and dense toxic fumes that prevented them from reaching the injured passengers. The station's sprinkler system was triggered, but it was not designed to suppress fire on the line itself. Therefore, it released water onto the platform and station passages, further inhibiting attempts to evacuate the station.

By the time firefighters discovered the remains of 70 people in one car, most had been reduced to ash and bones. Another 50 were discovered on the stairs of the station, apparently having choked to death as they attempted to flee the station. More than five hours after the fire started, firefighters with breathing apparatus were still hunting for survivors at the underground station.

Damage and Service Restoration

The fire was fueled by the train's vinyl interior, seat cushions, and flammable floor tiles and windows. Both of the six-car trains were demolished by the flames.

Subway Line 1 resumed normal business on February 26, 2003, except for the six stations around Jungangno.

Conclusions

Two days after the arson attack, South Korean President-elect Roh Moo Hyun declared the Daegu subway area a "Special Disaster Zone" so that it would be eligible to receive special administrative and financial aid for rescue work and restoration and for victims' compensation. Roh also ordered safety checks of the entire Daegu Metropolitan Subway System and said he would push ahead with the plan to establish a disaster control body to better cope with incidents like the arson attack. Investigators focused their probe into possible mistakes made by subway officials dealing with the emergency, concentrating on why the doors of the carriages of the two trains failed to open after the fire started.

Shortly after Roh's speech, subway officials promised to install emergency lighting, increase the number of exit signs, make car interiors flame resistant, and heighten security.

Kim Dae Han was apprehended 2 hours after the incident at a local hospital. He was transferred to Kyungpook National University Hospital to receive treatment for burns incurred during the incident. Police determined that Han showed signs of mental illness, for which he was treated between 1999 and 2002. He was a taxi driver who had become paralyzed on the right side of his body after what he considered faulty medical care. On the day of the incident, Han was determined to commit suicide in a crowded place. The Daegu District Court convicted him of arson and homicide on August 7, 2003, and sentenced him to life in prison. Although prosecutors had asked for the death penalty, the court showed leniency, saying that Han was repentant and mentally unstable when he committed the crime.

On February 24, 2003, police arrested 7 subway officials and announced that they were seeking 3 more warrants in connection with the arson. Among the 10 warrants, 9 were for subway officials and 1 was for the alleged arsonist. Among those who would be arrested that day and on March 4, 2003, for suspicion of professional negligence resulting in death and injuries was the driver of the original burning train and the driver of the second train who was suspected of pulling the master controller key out of the doors, trapping passengers inside the train as its cars filled with smoke and toxic fumes from the fire blazing in the other train. The charges were announced within weeks of a 63-year-old woman becoming the 198th fatality of the blaze when she died in an area hospital.

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3.2.3 St. Gotthard Tunnel Fire

Location:	Goeschenen and Airolo, Switzerland
Date:	October 24, 2001
Incident Category:	crash and fire (road tunnel)
Tunnel Length:	10.6-mile (17-kilometer) single-bore tunnel
Fatalities and Injuries:	11 fatalities, injuries not tallied

Synopsis

A head-on collision of two trucks—one carrying tires—about 1 mile (1.6 kilometers) from the tunnel's southern entrance sparked an explosion and subsequent fire. Additionally, part of the tunnel's intermediate ceiling collapsed over a distance of about 328 feet (100 meters). These two separate events combined to make the tunnel unapproachable because of temperatures as high as 1,832°F (1,000°C) and falling roof debris. Up to 40 cars and trucks were fused into a molten mass at the heart of the disaster zone. The incident resulted in 11 fatalities. Rescue efforts were hampered by the extreme heat and the risk that additional sections of the tunnel roof might collapse.

Analysis of Pre-Incident Information and Events

The St. Gotthard Tunnel is a 10.6-mile (17-kilometer) long, single-bore, two-lane tunnel linking the Swiss towns of Goeschenen in the north with Airolo in the south, approximately 10 miles (16 kilometers) from the Italian border. It holds two lanes of traffic in its 25-foot (7.8-meter) width, and when it opened to traffic in 1980, it was hailed as the safest of all the Alpine tunnels. Its safety features included a system of survival spaces at 820-foot (250-meter) intervals built to accommodate up to 70 people in an emergency; a safety corridor that parallels the tunnel length, allowing rescuers to quickly reach the scene of an accident (but too narrow for a rescue vehicle); and a state-of-the-art ventilation system that allowed a total air exchange every 15 minutes.

While approximately five fires per year had been reported in the tunnel, it was considered a safe route for motorists, especially after the March 1999 Mont Blanc tunnel fire. Traffic in the St. Gotthard tunnel had increased substantially after the March 1999 fire in the Mont Blanc tunnel that links France and Italy. At the time of the St. Gotthard incident, the traffic in the St. Gotthard tunnel averaged 16,497 vehicles daily.

In the wake of the Mont Blanc fire, prior to the St. Gotthard incident, safety campaigners had been saying that it was only a matter of time before such a disaster struck Switzerland. Safety advocates had demanded either a significant reduction in freight traffic or the construction of a second tube to the tunnel that would allow separation of the northbound and southbound traffic flows.

Analysis of the Incident

At approximately 9:45 a.m. on Wednesday, October 24, 2001, a southbound truck and a northbound truck that was carrying tires struck each other in a head-on collision at a spot located approximately 4,900 feet (1.5 kilometers) from the tunnel's southern end. Sparks from the collision ignited and spilled fuel from the trucks. Flames rapidly spread to the tires, resulting in thick black smoke that contributed to a zero-visibility level in the tunnel. The heat at the incident site rapidly climbed to 1,832°F (1,000°C), and it was later reported that explosions were heard as part of the ceiling collapsed from the intense heat.

Fatalities and Injuries

Both truck drivers involved in the initial accident were killed. There was speculation that one had been intoxicated and had questionable driving experience, but only one of the two bodies was in a condition sufficient to permit blood testing. Nine other people were killed, many seated in one of the 23 passenger vehicles involved in the accident. Some were burned to death as they called for help from their vehicles and others had most likely reached safety but returned to their vehicles to retrieve items left behind. Virtually all fatalities occurred within the "red zone," the 164-foot (50-meter) area nearest the seat of the fire. Vehicles were completely melted, and some were welded together.

Fire and Emergency Response

More than 300 people, including police, firefighters, and rescue workers, used five helicopters and 60 emergency vehicles in the rescue efforts, which were severely hampered by the extreme heat and the risk that additional sections of the tunnel roof might collapse. The fire smoldered for 24 hours and was finally put out more than 48 hours after it began.

Damage and Service Restoration

After the accident, police quickly closed the 10.6-mile (17-kilometer) tunnel. When Swiss President Moritz Leuenberger visited the site 24 hours after the incident, he described it as a scene of total destruction and expressed amazement that so many people had survived.

A team of 10 specialists spent the Monday following the incident combing through charred vehicles and rubble in search of victims in the "red zone." When the heat and smoke dissipated, crews began building metal supports to shore up the tunnel's weakened ceiling and walls. Police continued to check the tunnel to ensure there was no risk of the fire reigniting. Air quality checks were also conducted, and the experts were not allowed in until tests for poisons had been completed.

Later analysis found that safety systems worked well during the incident, with alerts sounding in four languages within minutes. Truck drivers, familiar with the tunnel, were reported to have directed other users to safety. In addition, approximately 656 feet (200 meters) of the tunnel were only superficially damaged and the primary concrete lining appeared unscathed. Regardless, the tunnel was closed for 2 months as engineers looked at every aspect of the infrastructure.

With the tunnel closed, Alpine communities that depended on traversing the Gotthard tunnel feared they would be cut off during the coming winter. To alleviate some of the tunnel traffic crisis, the Swiss federal railways increased the number of trains carrying trucks through the Alps by 20 to 30 percent. The number of trains carrying cars through the Lötschberg tunnel between the Swiss cantons of Bern and Valais were also increased.

The St. Gotthard tunnel reopened two months after the incident occurred, with a number of new safety rules in place, such as restricting the distances between trucks to 492 feet (150 meters) and abiding by an alternate one-way traffic system introduced to bring the St. Gotthard tunnel in line with other major tunnels in Switzerland. Two-way truck traffic was eventually reestablished, but a maximum of 60 to 150 trucks per hour are permitted through the tunnel at one time depending on the amount of traffic.

Swiss customs officials also began to hand out safety brochures to truck drivers, and the federal government worked with Swiss cantons to make tunnel safety part of truck drivers' training.

Conclusions

The St. Gotthard tunnel fire was the third major fire in 3 years in trans-Alpine, European tunnels. Although the safety level in the tunnel was considered quite high at the time of the incident, in its aftermath new safety rules were developed to reduce the number of trucks in the tunnel and their direction of travel from two-way to one-way, although two-way traffic has since been restored. By increasing the distances between vehicles and by ensuring that all vehicles traveled in the same direction, it was felt that the chances of head-on and rear-end collisions would be reduced, and therefore the chance of catastrophic fire in the tunnel would also be reduced.

The tunnel's ventilation system was also renovated to provide individually closeable and openable shutters.

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3.2.4 Howard Street CSX Tunnel Fire

Location:	Baltimore, Maryland
Date:	July 18, 2001
Incident Category:	derailment and fire

Tunnel Length:	single-track rail tunnel, 1.7 miles (2.7 kilometers) in length; approximately 4.8-percent upgrade
Fatalities and Injuries:	0 fatalities, 4 injuries

Synopsis

A 60-car freight train, of which eight cars in the rear half of the consist were carrying dangerous or hazardous materials, caught fire, probably because of a derailment in the Howard Street tunnel, located within the city of Baltimore. The train was stopped in the tunnel, and staff disconnected the three locomotives and escaped. There were no fatalities and only minor injuries, but the fire resulted in large quantities of smoke escaping the tunnel. The fire brought the city to a halt and resulted in a series of lawsuits by Baltimore against CSX.

Analysis of Pre-Incident Information and Events

The Howard Street tunnel opened in May 1895, when the Baltimore & Ohio (B&O) Railroad used it to carry freight through the city of Baltimore. The cost of the tunnel, known as the Baltimore Belt Line, drove the B&O into receivership in 1896, but the tunnel has been used ever since then as a major north/south freight route. Originally 1.4 miles (2.3 kilometers), an extension of 0.3 mile (536 meters) was added to the tunnel in the 1980s to accommodate parking for the Baltimore Orioles baseball stadium and a light rail station built at Camden Yards.

The tunnel, constructed mostly of concrete and refractory brick, is a single-track freight rail that travels for 1.7 miles (2.7 kilometers) through downtown Baltimore. It has vertical walls and measures 22 feet (6.7 meters) wide by 27 feet (8.2 meters) high, although the dimensions vary slightly along the tunnel's length. The tunnel's depth below grade varies from 3 feet (0.9 meters) to 60 feet (18 meters), and it has a 4.8-percent grade to account for the height difference of approximately 330 feet (100 meters) from the entrance to the exit at Mount Royal Station. At the time of the derailment, the train was moving in the direction of the upward grade.

Since the opening of Oriole Park Stadium and light rail at Camden Yards, the area has become a focal point for cultural and tourist activities. From July 13 to15, Artfest 2001 had drawn more than 250,000 people to the area. The area's popularity and its centrality to the vitality of Baltimore's business community played a large role in the traffic delays and loss of revenue that the derailment and fire caused in the city of Baltimore.

Analysis of the Incident

Shortly after 3:00 p.m. on Wednesday, July 18, 2001, CSX freight train L421216 derailed in the Howard Street Tunnel in Baltimore. The 60-car train was pulled by three locomotives and was traveling at 17 mph (27 kilometers per hour), below the speed limit of 25 mph (40 kilometers per hour). The train was halted by the emergency brake, indicating an air brake loss of pressure, which is designed to prevent the engineer from restarting the train until the air sensor on the last car detects sufficient pressure. The air hose, which runs the length of the train, was either severed or disconnected and caused the train to stop about half a mile (800 meters) from the northern end of the tunnel.

The train's crew, consisting of an engineer and a conductor, attempted to contact a CSX dispatcher, but their radio would not transmit inside the tunnel. One member of the crew used his cell phone to contact the CSX dispatch center in Jacksonville, Florida. The crew members then dismounted the locomotive and, as policy required, attempted to walk the length of the train to locate the problem. They were unable to do this because of the heavy black smoke that limited their visibility and made breathing difficult. The crew followed training and emergency procedures, shutting down the two lead locomotives and uncoupling the third from the train so they could exit the tunnel. Sensors indicated that they left the tunnel at 3:27 p.m. and called CSX to describe the emergency and report what they had done.

The train, traveling from Hamlet, North Carolina, to Oak Island, New Jersey, had 31 loaded and 29 empty cars. Eleven of the cars were derailed, including a tank car carrying about 28,600 gallons (108,000 liters) of liquid tripropylene, a lubricant similar to paint thinner. Fire officials believed that the derailment caused this car to rupture and fuel the fire. The train was also transporting tank cars that contained hydrochloric acid (a metal cleaner), glacial acetic acid (a flammable glass solvent), fluorosilicic or hydrofluoric acid (a noncombustible but corrosive acid used to fluoridate water), and ethyl hexyl phthalate (a combustible used to make a variety of flexible products, including piping). None of these chemicals were believed to have caught fire. The extreme smoke conditions were also attributed by Baltimore's fire department to wood products that the train had been carrying. This assessment was reinforced by air quality tests, which revealed mostly steam and hydrocarbons, common in wood fires.

Fatalities and Injuries

There were no fatalities; two firefighters were hospitalized after complaining of chest pains, and two workers were treated and released from the hospital for heat-related injuries on the day of the fire. Four emergency workers, two of whom were CSX employees, were rescued by fire personnel when one of them complained that his oxygen supply was running out.

Fire and Emergency Response

The response of Baltimore's fire department was delayed by the inability of the CSX crew to contact the dispatcher. The crew made contact with the dispatcher at 4:04 p.m., about an hour after the train had stopped in the tunnel and the crew had discovered smoke. The fire department arrived on the scene at 4:18 p.m. not in response to a report from CSX, but after receiving calls from the public reporting black smoke coming from either end of the tunnel and up through sewer covers.

One hundred and fifty firefighters worked to extinguish the fire, which by 5:15 p.m. had been raised to five alarms. Those who responded first tried to fight the fire by entering the tunnel from either end on vehicles with special rail wheels, but the intense heat and lack of visibility made this impossible. Instead, they lowered large-diameter hoses from the street above into the tunnel and were able to reach the burning cars after 10:00 p.m. To combat the smoke and heat, they used oxygen masks and air tanks and entered the tunnel on a sports utility vehicle outfitted with train wheels.

Firefighting efforts were complicated by the rupture of a 40-inch (100-centimeter) water main running directly above the tunnel; this rupture was reported at 6:25 p.m. The rupture resulted in the collapse of a number of city streets. It also flooded nearby buildings, halted electricity to about 1,200 customers of Baltimore Gas and Electric, and interrupted a major Internet cable line and an MCI WorldCom fiber optic telephone cable.

At about 5:45 p.m., the city had activated civil defense sirens to warn citizens of danger from the fire and the hazardous materials. A number of key local streets were shut down, including Howard Street between Pratt and Mount Royal streets, and parts of Lombard Street, a major downtown thoroughfare that collapsed following the water main rupture. All major highway entrances into Baltimore were closed by city officials, and baseball games at nearby Camden Yards were postponed because of the smoke emanating from both ends of the tunnel and through the sewer covers, which caused a black cloud over parts of the city.

The Baltimore City Police Department, assisted by the Baltimore Department of Public Works, controlled traffic on surface streets and closed highways I-395 and I-83 and US-40 into the city to preclude greater traffic congestion. As was mandated, notification of the presence of hazardous materials on the train was given to the Maryland Department of the Environment's Emergency Response Division. Within 2 hours of the start of the fire, the U.S. Coast Guard closed the Inner Harbor, which is a few blocks from the derailment location, to boat traffic. The Maryland Department of the Environment set up booms to minimize any possible contamination from the chemicals escaping from the rail cars involved in the fire.

The city's fire department was assisted by the Anne Arundel County Fire Department, which sent a dozen firefighters, two engines, and a truck to cover south Baltimore stations in the event of secondary emergencies.

In addition to CSX, the Maryland Transportation Authority (MTA)—which includes local bus, commuter bus, MARC, Metro subway, and light rail—became involved in emergency response. MARC personnel initiated bus service in the area when trains were unable to pass through. The MTA's Central Light Rail Line, which runs above the Howard Street tunnel, was disrupted, as was MTA bus service, which also runs along Howard Street. Also affected was the Metro, the MTA-managed subway system, which passes below Howard Street and the Howard Street tunnel.

On the third day, CSX contractors began pumping acid from two of the cars and replacing the 800 feet (243 meters) of track at the south end of the tunnel that had been damaged while removing the railcars. The fire burned for an additional 2 days; it was not fully out until 5 days after the derailment.

Damage and Service Restoration

It took 5 days for the fire to be totally controlled and for all rail cars to be removed from the Howard Street tunnel. Recovery efforts continued for 55 days. The final work was the completion of road repairs on September 10, 2001.

Because of the central location of the fire and the concern that hazardous materials might explode, rail and other transportation modes in Baltimore and beyond were disrupted. Within Baltimore, street closures in the Howard Street area cut traffic to the central business district and to the Inner Harbor tourist area. Passenger cars, commercial traffic, and buses were also affected. Howard Street was reopened to traffic on July 23 except in the area of the water main break, which was not completely repaired until July 29.

The MTA Metro's State Center Station (which was the closest station to the fire) was closed because of the smoke, although trains maintained their schedules without other service disruptions. The station reopened on July 20. The MTA light rail service was disrupted because of the water main break; bus service was initiated within an hour of the discovery of the water main break to move passengers around the disrupted stations. All bus routes that crossed Howard Street were turned back or diverted. While some of the diversions and delays were of short duration, others persisted for lengthy periods. For instance, full service on the MTA's light rail line was not restored and substitute bus service was not discontinued until September 8, which was 56 days after the derailment and fire.

The closing of the Howard Street tunnel affected freight moving between Chicago and the east coast, some of which was rerouted via Selkirk, New York, and South Kearny, New Jersey. CSX also used tracks owned by Norfolk Southern to minimize delays.

Much of Baltimore's business area was affected by the incident. In October 2001, CSX paid the city $1.3 million to cover some of the costs, primarily the overtime for police, firefighters, and public works department employees. The payment did not include the costs of cleaning up the chemical spill, investigating the incident, replacing the ruptured water main, or repairs to damaged roads. CSX's insurance adjuster accepted claims from 25 merchants on Howard Street for damages and lost business and paid $20,000 to a business improvement district operating in the area. CSX also paid $15,000 to volunteer groups that served meals to rescue crews responding to the incident.

The Baltimore Orioles baseball organization was also affected. A double-header was being played at Camden Yards Stadium at the time of the incident. The second game was cancelled, and all Orioles personnel and fans were evacuated. The next day's game was cancelled because of the smoke and traffic disruptions in the area. The team postponed four games scheduled in the following 3 days; no scheduled game was played until July 21. An Orioles' official estimated that the postponed games resulted in a financial loss to the team of $3 million.

An unusual side effect of the incident caused problems for the state of Michigan's campground and harbor reservation system when a Department of Natural Resources cable and telephone system located in Cumberland, Maryland, discovered that callers to 800-44-PARKS were either getting a busy signal or were forced to endure far longer waits for an operator than usual.

Conclusions

This incident presented three interrelated problems to all the emergency responders, but particularly to the Baltimore City Fire Department, which committed the largest number of people to the emergency response effort and had direct responsibility for fighting the fire that the derailment caused. The fire department worked closely with the department of public works to contain the water main break that occurred directly above the fire. In addition to having to fight a fire in a tunnel that was too dark and smoky for them to enter, the firefighters were faced with the presence of hazardous materials and with the weakened structural integrity of the water main and surrounding areas. The tunnel remained intact throughout the incident and was reopened to rail freight traffic once debris was cleared away.

Based on a model created after the fire, it was estimated that peak temperatures in the tunnel had reached approximately 1,832°F (1,000°C) in the flaming regions and approximately 932°F (500°C) when averaged over a length of the tunnel equal to three or four rail car lengths. Because of the insulation provided by the brick walls of the tunnel, the calculated temperatures within a few car lengths of the fire were relatively uniform, similar to an oven or a furnace. The peak wall surface temperature reached about 1,472°F (800°C) where the flames were directly impinging and averaged 752°F (400°C) over the length of three to four rail cars. Firefighters attempting to enter the tunnel lost all vision within 300 feet (91 meters) of the entrance; the use of self-contained breathing apparatus (SCBA) became essential when gas masks and air-purifying respirators (APRs) were found to be useless.

Despite the emergence of a number of issues—including tunnel access, the presence of hazardous materials, freight and other transportation delays, and the need for environmental monitoring—most analyses of the emergency response were positive. The potential for disaster was great; the fire department was not advised of the fire for an hour after it occurred, and the water main break could not have been anticipated, but once agencies were notified, they worked well together. The delayed notification by CSX to the fire department doubtlessly added to the financial cost of the incident, but the fire department was aided by CSX employees at the scene, who had a complete waybill that identified the location and contents of all cars and that was immediately shared with the fire incident commander on the scene.

The city agencies were able to work together and rely on mutual aid pacts that had been developed earlier. CSX also worked closely with the city agencies, contracting for a private firm to conduct air and water monitoring and providing all other information as needed. Response by fire department personnel was aided by a drill that had recently been conducted in one of the city's Amtrak tunnels using a MARC train and by previous drills in a Metro tunnel. Although these training exercises were intended to practice response in the event of a passenger train accident, they acquainted fire personnel with the environment of a railroad tunnel, which helped them in their response to a somewhat similar freight incident.

The major criticism of the handling of the incident pertained to information access, attributed to the failure to designate a public information officer during the initial stages and to the problematic internal and external communications by CSX.

On January 5, 2005, the National Transportation Safety Board's (NTSB's) recommendations R-04-13 and -14 indicated that CSX maintain historical records documenting inspection and maintenance activities affecting the tunnel and that the corporation take whatever steps necessary to exchange information with the city of Baltimore on maintenance and construction activities within and in the vicinity of the tunnel. Recommendations R-04-15 and -16, issued the same day to the city of Baltimore, reiterated the need for better cooperation and information exchange between CSX and the city and called on the city to update its emergency preparedness documents to include information on hazardous materials discharge response procedures specific to tunnel environments and to include infrastructure information on the Howard Street tunnel.

On January 13, 2005, the NTSB reported that it was unable to determine the cause of the incident. The report concluded, however, that according to a finite element analysis, the 40-inch (100-centimeter) water main above the tunnel broke after the train had derailed, as a result of the thermal expansion of the tunnel caused by the postaccident fire within the tunnel. Although the report was approved unanimously by the five members of the board, two board members were critical of the length of time the investigation took and the lack of attention to the security implications of shipping hazardous materials.

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3.2.5 Kitzsteinhorn Tunnel Cable Car Fire

Location:	Kaprun, Austria
Date:	November 11, 2000
Incident Category:	fire
Tunnel Length:	2.2 miles (3.5 kilometers); 45-degree inclination; single-bore tunnel designed for cable conveyance; very small cross-sectional area (108 square feet [10 square meters])
Fatalities and Injuries:	155 fatalities (152 of the total 167 passengers), injuries not tallied

Synopsis

The cable car's rear driver's cab caught fire at the bottom of the tunnel immediately after departure, causing a fire that engulfed a cable train packed with skiers in a tunnel on the 2.4-mile (3.9-kilometer) mountain. The fire caused the cable car to halt 1,970 feet (0.6 kilometers) inside the tunnel. Lights went out, and initially the doors would not open. Some doors were eventually opened, but the narrow 11.8-foot (3.6-meter) width left little space for evacuation. The steep (45-degree) incline turned the tunnel into a chimney, blocking the escape route.

Analysis of Pre-Incident Information and Events

The Kitzsteinhorn glacier, which rises to 2.4 miles (3.9 kilometers) in the Austrian Alps, is a popular international ski resort accessed via the city of Kaprun, 50 miles (80 kilometers) southwest of Salzburg, Austria. It is a 3-hour drive from Munich, Germany. Access to Kitzsteinhorn's ski trails is mostly via a circa 1976 funicular (i.e., cable) railway that originates at the Kaprun Valley station, climbs the slope, and enters a tunnel pass before emerging at the Kitzsteinhorn ski slopes. Access to the 2,900-inhabitant town of Kaprun is via one main road. The cable railway was modernized in 1994, adding two state-of-the-art cars and ancillary technology. At the time of the fire, the cable railway could transport about 1,500 people per hour up to the Alpine center on the glacier.

Several other incidents occurred in Alpine tunnels or to Alpine trains prior to the Kitzsteinhorn fire. These included the 1999 Mont Blanc Road Tunnel fire that killed 41 people; a 1999 fire in the Tauern motorway tunnel that killed 12 people and injured 50 people; and a 2000 accident in Germany in which two trains collided near the Zugspitze, injuring more than 60 people. After the Mont Blanc incident, inspectors visited 25 of the continent's biggest road tunnels and found that nearly a third had poor safety features.

The day of the accident—Saturday, November 11, 2000—was the first official day of the ski season. The funicular had undergone safety checks by an outsourced inspection agency 2 months prior to opening day. The last inspection by the government's Ministry of Transport had been in 1997.

Analysis of the Incident

On November 11, 2000, the Kitzsteinhorn funicular departed its base station in Kaprun with 167 passengers (near its 180-person capacity) and ski and snowboard gear en route to the Kitzsteinhorn glacier ski slopes. Before the cable car entered the 2.2-mile (3.5-kilometer)-long and 11.8-foot (3.6-meter)-wide tunnel, which had an average incline of 45 degrees, passengers and the driver noticed smoke emanating from the driver's cab. Although the driver reported the blaze to his base station, the train continued into the tunnel, stopping 1,970 feet (600 meters) from the entrance.

The fire continued and the steep tunnel acted like a giant chimney, sucking air in from the bottom and sending toxic smoke billowing upwards. Despite an alarm signal and contact with the base station instructing the driver to open the doors, the train stayed at the location with its doors sealed. Later investigation revealed that this was the immediate cause of death of most of the passengers.

A few passengers were able to knock out the windows to flee, but they were trapped between the fire below them and the smoke-filled tunnel ahead of them, with no clearly marked emergency exits. Of those who apparent climbed out of smashed windows and ran downhill, away from the smoke, only 12 survived. Others who fled uphill were overcome by smoke and fumes, most likely because of the small (approximately 108-square-foot, or 10-square-meter) cross-sectional area.

Fatalities and Injuries

One hundred and fifty-five fatalities were reported, 152 of whom were passengers on the funicular and 2 of whom were passengers overcome by smoke inhalation while waiting in an area outside the tunnel, and one who was a cable car attendant traveling in an empty car in the opposite direction. Those who tried to escape upwards were caught by smoke and warm gases and died inside the tunnel. The 12 people who survived escaped the train at an early stage through a broken window and fled downward in the tunnel. Recovery efforts were slowed by falling rock and toxic fumes.

Fire and Emergency Response

A massive rescue operation was mounted with approximately 13 helicopters and more than 200 emergency workers, including teams of police, doctors, and Red Cross workers. Rescue helicopters carrying firefighters with special equipment were also flown in from Bavaria. The Red Cross assembled a team of 40 psychologists to help relatives cope with their grief.

It took at least 3 hours to extinguish the fire, but fumes and smoke continued to emanate through the night. Rocks also fell from the tunnel walls, hampering rescue efforts throughout the incident.

Damage and Service Restoration

The cable cars and ski lifts at Kitzsteinhorn resumed operation on December 7, 2000, but the funicular Gletscherbahn Kaprun 2 remained out of order. During the month-long closure, an estimated $140 million in tourist revenue and local income was lost, since 80 percent of the area's jobs depend on tourism. Upon reopening the alternative means to the ski slope, revenues ran 40 percent less than prior to the funicular closing because 40 percent fewer skiers could be transported via alternative means.

The ÖBB, the Austrian Railways, received a court order on December 29, 2000, to save the wreck of the destroyed cabin. The process cost about 7 million Austrian Schillings (ATS) and was completed in early March 2001. The wreck was shipped to a laboratory, and all aspects of the analysis were filmed for the investigation.

Sixteen people—including cable car company officials, technicians, and government inspectors—were arrested and charged with criminal negligence. On February 19, 2004, the Austrian court acquitted all 16, but prosecutors immediately appealed the verdicts. Lawyers for the families said they would continue civil proceedings in the United States and Germany, seeking millions of dollars in compensation. These cases are still pending.

Conclusions

The official results of the investigations on the accident became known on September 6, 2001, when experts announced their belief that the fire was started by an electric heating ventilator illegally installed in the driver's cabin. On the day of the accident, the ventilator overheated, most likely at the lower station. A leaky tube of hydraulic oil came into contact with the glowing heater, nearby wooden panels, and isolation materials. These things became soaked with oil and caught fire, either in the departure station or on the way up the mountain.

Austrian investigators found that the ski train suffered technical problems before it entered the tunnel. They based their analysis on plastic-like debris found on the rails near the tunnel mouth that indicated that a fire could have broken out before the train went into the tunnel.

Investigators also pointed out that a larger cross-sectional area might have given the passengers more time for evacuation.

Officials in ski resorts throughout Austria shut down five similar train systems for safety checks following claims that the Kitzsteinhorn train was not properly fitted with safety devices, such as a sprinkler system, and did not have enough emergency exits or fire extinguishers. An allegation was made that an evacuation drill had never been carried out. In direct response to the incident, the French government announced that it would institute immediate safety checks on all its funicular railroads.

The incident had parallels with the 1987 King's Cross Tube Station fire in London, where the escalator shaft at the center of the fire had a 30-degree incline that, like the Kitzsteinhorn tunnel fire, created a chimney effect. The Kitzsteinhorn blaze moved faster than the King's Cross fire because of an even steeper incline.

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3.2.6 Mont Blanc Tunnel Fire

Location:	Chamonix, France/Courmayeur, Italy
Date:	March 24, 1999
Incident Category:	fire
Tunnel Length:	7.3 miles (11.6 kilometers); single-bore, reinforced concrete; two traffic lanes; 28-foot (8.6-meter) width
Fatalities and Injuries:	39 fatalities, injuries not tallied

Synopsis

A truck carrying margarine and flour entered the 7.3-mile (11.6-kilometer)-long Mont Blanc Tunnel from France, caught fire, and stopped in the tunnel, where it burst into flames. The fire, which was fueled in part by the margarine, reached temperatures of 1,832°F (1,000°C), trapping approximately 40 vehicles in dense and poisonous smoke.

Analysis of Pre-Incident Information and Events

The Mont Blanc Tunnel is a major Alpine automotive tunnel connecting the cities of Chamonix in Haute-Savoie, France, and Courmayeur in Valle d'Aosta, Italy. Situated under the highest mountain in Europe, the Mont Blanc massif, the tunnel was notable for its approach to ventilation and was the first large rock tunnel to be excavated full face, with the entire diameter of the tunnel bore drilled and blasted. It was operated by two separate agencies, the Autoroutes et Tunnels du Mont Blanc (ATMB) in France and the Società Italia per l`Esercizio del Traforo del Monte Bianco (SITMB) in Italy. Although ventilation and safety systems existed on both sides and were operated by French and Italian personnel, the systems differed in a number of ways and there was little consultation between the two agencies.

Begun in 1957 and completed in 1965, the tunnel is a major trans-Alpine transport route, particularly for Italy, which relies on the tunnel to ship as much as one-third of its freight bound for northern Europe. For the French, it is a passage for exports to Italy and a tourist route to the south. It was designed to carry 450,000 vehicles per year, but by 1997 it was being used by 1.1 million vehicles per year. In 1974, one person was injured in a truck fire that lasted about 15 minutes; in 1990, two people were injured when a fire occurred in a truck loaded with cotton.

Lay-bys are located every 300 meters, alternating on each side of the carriageway, and numbered 1 to 36 from France to Italy. In front of each one, a gallery makes it possible for heavy-goods vehicles to do U-turns. Shelters supplied with fresh air and protected from the tunnel by a wall with a 2-hour fire rating are located every 600 meters.

Analysis of the Incident

Wednesday, March 24, 1999, was a day with average traffic flow in and out of the tunnel. Between 9:00 and 10:00 a.m., about 165 vehicles drove from France to Italy. This traffic translated to roughly four vehicles per minute entering the tunnel and traveling at 50 mph (80 kilometers per hour), with an average of 980 feet (300 meters) between vehicles. Weather conditions were normal; rain clouds had cleared and the warm southern wind called die Föhn blew from the Italian side of the tunnel. A medium wind blew, as usual, inside the tunnel from south to north.

One of the trucks that entered the tunnel from the French side was a Volvo FH12 tractor-trailer driven by Gilbert Degraves, a 57-year-old Belgian trucker with 25 years of experience. He was hauling a refrigerated trailer loaded with nine tons of margarine and 12 tons of flour. Although nothing abnormal was visible to the driver, later investigations estimated that the fire started about 10:46 a.m. and was fueled by the 145 gallons (550 liters) of diesel in the truck's tank.

At 10:53 a.m., Degraves was alerted that something was wrong when he noticed that oncoming cars were flashing their headlights at him. Through his rearview mirror, he saw white smoke on the right side of his truck, and stopped at Mile 3.8 (Kilometer 6.2). After allowing a truck coming from the opposite direction to pass, he exited his vehicle. He stated later that he had tried to reach the fire extinguisher under the left seat to extinguish a fire between the cab and the trailer, but flames had burst out on both sides of the cab.

Other truckers noticed white smoke swirling toward the tunnel's ceiling at 10:56 a.m. At about the same time, automatic video cameras detected cars turning into Lay-By 22. People on foot were also visible there. Between the time the Belgian truck entered the tunnel and the time it was closed to traffic 9 minutes later, 1 motorcycle, 10 passenger vehicles, and 18 trucks had also entered the tunnel. Four trucks passed the burning truck after it had stopped, and 26 vehicles were trapped.

At 10:54 a.m., the Italian control room was informed by phone that smoke had been detected on the video monitors between Lay-Bys 16 and 21. The siren on the French side went off at the same time. A minute later all traffic lights in the direction from France to Italy turned red and a truck backed up to yield to emergency vehicles, although two other vehicles continued into the tunnel.

The obscuration detector in Lay-By 18 set off a visual and audio alarm at the French control station. The operator at the control station acknowledged the alarm. Observation of cameras in Lay-Bys 16, 17, 18, and 19 indicated that smoke had surrounded the truck.

Although the French fire detection system in the tunnel had heat sensors every 26 feet (8 meters) programmed to sound when temperatures rose over 122°F (50°C), it did not sound an alarm while the burning vehicle was moving. The first French alarm sounded at 11:13 a.m. from Lay-By 19. By then, temperatures were estimated to have been higher than 1,832°F (1,000°C). The Italian detection system relied on 230- to 260-foot (70- to 80-meter) sealed tubes containing a special gas. The system had been prone to false alarms, and, because the tubes at Lay-By 21 (where the truck stopped) had given false alarms the night before, they were off and could not signal any fire.

The smoke changed almost immediately from white to black, and the fire quickly entered the cab. The trailer, which was constructed of flammable isothermal foam, caught fire later. The cargo of margarine was transformed into a combustible liquid as it melted and ran out of the trailer and spread onto the road.

On the Italian side, the drivers of the eight trucks that had stopped before Lay-By 22 left their cabs when they observed black smoke. The tunnel is too narrow for trucks to make a U-turn, so the drivers fled on foot. All escaped, possibly because the airflow from Italy to France was blowing the smoke away from them. Drivers on the French side left their vehicles and ran back toward the French entrance. They died, probably of toxic smoke, between 660 and 790 feet (200 and 240 meters) from the fire. The majority of drivers on either side further away from the fire stayed in or near their vehicles; 27 were found dead in the wrecks, nine were found outside their vehicles. It took no more than 10 minutes for the tunnel to fill with combustion gases.

Fatalities and Injuries

Thirty-nine people died, including one firefighter. Post-incident analysis determined that most died within 15 minutes of fire detection. Of the 38 nonfirefighters who died, 27 stayed in their vehicles, 2 took refuge in another vehicle, and 9 died outside their vehicles. Of these 9, a motorcyclist and a car driver died in Shelter 20 near the fire zone.

Fire and Emergency Response

Emergency response was provided by tunnel employees and fire departments from France and Italy. A French employee coming from Italy drove past Lay-By 22 and crossed a thick wall of smoke that filled the whole cross section for a distance of 330 to 660 feet (100 to 200 meters). He reached within 33 feet (10 meters) of the burning truck as an Italian employee came from the opposite side. This Italian employee on the French side at 10:56 a.m. likely drove a motorcycle into the tunnel, where he encountered people fleeing on foot. He advised them to keep to the side with the fresh air outlets and he continued to drive wearing a breathing device. He got within 23 feet (7 meters) of the Belgian truck and saw a burning cab and lamps and cables tumbling down from the ceiling. He returned to the French side to report this, and then reentered the tunnel to help more people. He reportedly saved at least 10 people from death but was unable to save himself; he died at Shelter 20 along with a driver from a passenger car.

Fire department responses began 11 minutes after the fire, when, at 10:57 a.m., a pumper engine with four firefighters, extinguishers, and breathing devices; a rescue vehicle with additional equipment; and an ambulance entered the tunnel from France. When the French Central Alarm Center was alerted to the fire at 10:58 a.m., it forwarded the alarm to the Main Rescue Center in Chamonix at the same time that an alarm was pulled at Lay-By 21. At the time, the four French firefighters, who were 1,100 yards (1,000 meters) from the burning truck, reported zero visibility. They were ordered to take shelter in Shelter 17. Although the shelters can hold dozens of occupants, the bunkers were designed to resist heat and toxic fumes for only about 2 hours.

The Italian side initially dispatched eight motorcycle patrols and a multi-use fire vehicle with three extinguishers staffed by a driver. Italian firefighters were alerted to the fire at 11:02 a.m. and arrived at 11:10 a.m. The Italian fire detection system lost all transmission data in Lay-By 19, although Italian firefighters arrived at the portal on their side. At Lay-By 22, they were stopped by heavy smoke. Although they tried to continue on foot, the extreme heat and low visibility forced them to retreat.

Approximately 30 minutes later, a second engine arrived at the French portal, but was unable to rescue the first group of firefighters because of the smoke condition. The fire engines could not be removed from the tunnel until 3 days later; at that time, one engine was found totally burned and the other badly damaged. About 3 hours into fighting the fire, the French commander raised the alert to red (the highest level possible) to permit a higher level of firefighting machinery to be employed. Both nations' firefighting efforts were hampered when, by 11:01 a.m., the lighting equipment, the French sprinkler system, and the Italian exhaust dampers failed in the tunnel.

At just short of 8 hours into the incident, French firefighters rescued six people in Shelter 17. This was the final rescue that firefighters were able to mount.

Although the tunnel originally was constructed with a full transverse ventilation system, by the time of the fire the system was transformed into semi-transverse ventilation that was limited to exhausting air. The change had been made to accommodate the increased truck traffic in excess of what had been anticipated at the time of construction, since the traffic mix called for a greater amount of fresh air.

When the Italian operator saw people fleeing on foot, he judged that it was preferable to introduce oxygen to give those people a chance instead of switching the ventilation to maximum extraction. The added oxygen helped the flames spread rapidly and created a strong blow of toxic smoke towards the French side. The French extraction capacity was insufficient to get rid of this air, so it blew right through the tunnel. Since no one was injured on the Italian side, the decision may have saved some people, although it probably added to the deaths on the French side. Nature also played a role: As the incident unfolded, an air stream (Föhn) blew from the Italian to the French side.

Investigators later reported that the tunnel operators knew of deficiencies in the ventilation system but had done little to correct them. The problems were exacerbated by gases that were present in the tunnel, the foam insulation of the trailer that produced nitrogen oxides, and the burning margarine; all of these things were worsened by a lack of oxygen, which led to the production of more toxic gases.

Damage and Service Restoration

It took more than 50 hours for the fire to be completely extinguished; it required a spray mist to cool the interior sufficiently for entry to move the concrete, burned installations, and truck cargo that blocked access to the center of the tunnel. The shelters near the incident were also severely damaged. In addition, nearly 1,100 yards (1 kilometer) of the tunnel lost virtually all its ceramic tiles.

As a result of the fire, the tunnel was closed for 3 years while numerous safety features were installed.

There was local opposition to the tunnel's reopening based on claims of danger from truck exhaust fumes and concerns that truck traffic polluted the Alpine region. Protesters blocked the first heavy freight truck trying to use the tunnel and set fire to its contents when they found a television crew aboard the largely empty Belgian truck. After three cancelled openings, the tunnel reopened in stages: to cars in March 2002, to trucks with up to four axles and weighing less than

19 tons in May 2002, and to all trucks in July 2002 (despite a July 26, 2002, environmental protest against reopening the tunnel to heavy goods vehicles).

Conclusions

The inquiry into the 1999 Mont Blanc fire led to a radical reassessment of safety needs, a redesign/rebuilding of the tunnel, and a restructuring of the tunnel management. Investigators determined that communication between the French and Italian sides of the tunnel had been very limited and that almost no coordinated efforts had been made in any area. Neither the Italian fire service nor the French fire service had ever mounted a full exercise inside the tunnel. Two joint safety exercises had been held in 25 years, and neither had involved live practice inside the tunnel. No joint fire drills had been held in the 10 years prior to the incident. The investigation also determined that both nations' emergency plans—the French plan from 1994 and the Italian plan from 1995—were inadequate and lacked any redundant or failsafe systems.

A significant management change resulted from the fire. Now, one company that includes both French and Italian interests manages the entire tunnel, with one active control room and one incident commander. The general manager changes every 30 months and alternates between countries. Full-scale, videotaped safety training exercises are conducted every 3 months to improve organization and cooperation among the rescue services, including firefighters, paramedics, and police from both countries. 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.

Numerous other safety measures emerged from the court inquiry that were intended to detect abnormal situations, provide protection and evacuation routes for tunnel users, provide access for rescuers, and assist in the self-protection of tunnel users and firefighters. To achieve these goals, the tunnel authorities made numerous improvements:

- Installing lay-bys and turning bays every 1,970 feet (600 meters) on both sides of the tunnel to allow heavy goods vehicles to stop and to allow maintenance and rescue vehicles to operate in the tunnel.
- Situating concrete-lined emergency shelters on one side of the tunnel at 980-foot (300-meter) intervals to protect occupants from the atmosphere of the tunnel. Each shelter is pressurized and fitted with a fireproof, airlock door. The shelters are also equipped with telephones, closed-circuit TV cameras, video links to one of three command posts, and public address systems.
- Adding 116 smoke extractors, one every 328 feet (100 meters), and creating 76 new fresh air vents.
- Adding fire-resistant sheeting to the tunnel's walls.
- Installing more traffic lights and flashing warning signs along the tunnel.
- Installing new heat sensors at both ends of the tunnel to detect overheated trucks before they enter the tunnel.
- Adding 120 video cameras to monitor traffic at all times.
- Locating firefighting facilities at each portal and one close to the tunnel's midpoint.
- Restricting truck travel to one direction through the tunnel. Trucks traveling in the opposite direction must use the Frejus Tunnel some 55 miles (90 kilometers) to the south.

On January 31, 2005, a criminal trial to establish responsibility for the fire began in France. Sixteen people and companies were named as defendants in the manslaughter case, including the Belgian driver of the truck that caught fire; Volvo, the truck's manufacturer; both the Italian and French companies that managed the tunnel; safety regulators; and the mayor of the town of Chamonix. The French court found 12 individuals and four companies guilty of manslaughter. The head of tunnel security received a 6-month jail term plus a 24-month suspended sentence; the president of the French operating company received a 2-year suspended jail term plus a fine; and the driver of the truck received a 4-month suspended jail term. Seven other people, including the tunnel's Italian security chief, were handed suspended terms and fines. Three companies were fined up to $180,000 each. The charges against Volvo were dropped.

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3.2.7 Channel Tunnel Fire

Location:	Folkestone, England/Sangatte, France
Date:	November 18, 1996
Incident Category:	fire
Tunnel Length:	32-mile (50-kilometer) twin-bore steel and concrete underwater tunnel with access to a service tunnel every 1,230 feet (375 meters)
Fatalities and Injuries:	0 fatalities, about 30 injuries

Synopsis

A freight truck on Train 7539 traveling from France to Great Britain caught fire in the Channel Tunnel. The train continued at normal speed (120 kilometers per hour) for about 10 minutes before it stopped next to an exit to the adjoining service tunnel, where it became impossible to disconnect the burning part of the train. The heavy fire damaged the power catenary quickly once the train stopped. The fire then spread rapidly to adjoining cars. The smoke moved quickly because of other trains moving in the tunnel; this smoke also hampered evacuation. Train staff and truck drivers evacuated through a door leading to the service tunnel, but overpressure from that tunnel door created a fresh air bubble when the door was opened. All crew and passengers were rescued via the adjoining service tunnel; structural damage was considerable.

Analysis of Pre-Incident Information and Events

The Channel Tunnel is a 32-mile (50-kilometer) rail tunnel hundreds of feet beneath the English Channel that connects the United Kingdom with France. It is the world's longest undersea tunnel. Despite the tunnel's length, it is possible to travel through the tunnel in about 20 minutes because trains may operate at speeds up to 100 mph (160 kilometers per hour). Construction began in 1988; by the time the tunnel was completed in 1994, it had cost more than $21 billion to complete, making the tunnel the most expensive construction project undertaken at that time. Also called EuroTunnel, Eurotunnel, or the Chunnel, it is actually three tunnels. Two of the tunnel tubes are full size and accommodate rail traffic. Between these tunnels is a smaller service tunnel that was planned as an emergency escape route. There are also crossover passages that allow trains to switch from one track to the other.

Each running bore has a walkway on the side nearest the service tunnel that was designed specifically for the evacuation of passengers and crew in an emergency. The running tunnels are connected by cross passages to the service tunnel at about 1,230-foot (375-meter) intervals. The passages have fire-resistant, air-lock doors on each side.

Although the Eurostar train, the passenger service through the tunnel, received most of the early publicity, the Channel Tunnel is primarily a conduit for freight. In the first 5 years of the Channel Tunnel's operation, trains using the tunnel carried 28 million passengers and 12 million tons of freight.

Trains carrying freight through the Channel Tunnel are different from U.S. trail vans, where freight vans are loaded onto flatbeds and carried solely by the train to an unloading yard. Although the Channel Tunnel provides a rail-only link, drivers of trucks load their vehicles onto specially designed carriers and then leave their trucks to ride in coaches that are usually located next to the locomotive and away from the trucks, which are generally at the end of the train. When the train arrives at its destination, the trucks are unloaded from the train and the drivers retrieve their trucks and proceed to their destinations.

This fire was not the first fire in the tunnel. About a year after it opened, the Channel Tunnel was the scene of a fire that broke out in a train going from France toward England, as was the case in the November 18, 1996 fire.

Analysis of the Incident

A truck carrying expandable polystyrene (EPS) caught fire on Train 7539 traveling through the Channel Tunnel from France to the United Kingdom on November 18, 1996. It was one of 29 trucks on the train, which was about 11 miles (18 kilometers) into the tunnel when the fire was discovered. EPS, which is saturated with the expanding agent pentane, is flammable and is shipped in the form of beads in large bags or drums that are frequently transported by truck. Although most hazardous substances are prohibited from transport through the tunnel, EPS was not among the banned substances.

The fire, which began near the end of the train, where the loaded trucks were located, filled the tunnel with smoke and reached temperatures of 1,832°F (1,000°C), which resulted in a number of the truck-bearing railcars being welded to the track.

The train driver was unable to follow Eurotunnel's primary safety option of proceeding through the tunnel in an emergency. The passenger carriage and front locomotive should have automatically uncoupled from the train, but a power failure prevented this automatic uncoupling from occurring. This failure forced the train crew to lead the passengers off through the central tunnel. The rescue effort was estimated to have taken about 20 minutes. From the center tunnel, the evacuees were put on a train that traveled through the second tunnel tube to safety.

The tunnel was busy at the time; in addition to the train that caught fire, other vehicles in the tunnel included two Eurostar passenger trains, two tourist shuttles, and two other freight shuttles (or lorry shuttles, as they are called in Great Britain). Once the fire was confirmed by the command center, one of the tourist shuttles in the non-incident tube was ordered to stop at one of the fire doors to evacuate 26 passengers and the engineer of Train 7539.

Fatalities and Injuries

The 29-car train was carrying 31 passengers and a crew of three; people who were injured suffered smoke inhalation, mostly while being evacuated through the service tunnel. Nineteen people were treated at hospitals, and two were seriously injured. Others received medical attention at the scene.

Fire and Emergency Response

It took firefighters from both countries almost 14 hours to contain the blaze, which damaged about 1,970 feet (600 meters) of the tunnel. In addition, the concrete lining was scorched, miles of power cable were destroyed, and a section of the track buckled. The fire also destroyed the rear locomotive and nine trucks.

Damage and Service Restoration

Partial restoration of service took place on November 21, three days after the fire occurred, but the United Kingdom–bound tube, where the fire occurred, was not reopened to passenger trains until about a month after the incident.

Conclusions

Although safety procedures called for a train to speed through the tunnel if fire broke out, the train stopped in this instance. Additionally, although procedures called for the emergency ventilation system to be switched on, the system was not activated. Despite the sophisticated ventilation system built into the Chunnel to pull smoke from the running tunnels and to provide air to the service tunnel, the system did not work as designed during the fire. Three problems were later determined to have prevented the system from activating; two were caused by equipment and one by human error. The first mechanical problem occurred when the heavy steel doors used to close off the tunnel crossovers remained in the open position during the incident. The second mechanical problem occurred when one piston relief damper did not close as it should have. These problems led to the large amount of smoke in the non-incident tunnel, and that amount of smoke was increased when the variable-pitch fans were left at zero pitch, making them useless for several minutes. Once this problem was corrected, the fans helped to remove smoke from the tunnel quickly.

There was extensive damage to the tunnel's concrete lining, about 1,970 feet (600 meters) of which was scorched by the fire and spalled under the intense heat. Similar damage did not occur in other tunnel fires, and this difference led to considerable study of the materials used and the heat-resistant qualities of tunnel liners.

Firefighters and some safety experts voiced concern about the design of the railcars that carry the trucks through the tunnel. The railcars are considered semi-open and are lighter than the closed railcars that carry passenger vehicles and small trucks. The semi-open railcars permit a free flow of air that may spread a fire. Since drivers do not remain with their trucks, it may be some time before a fire is observed and its exact location noted. Conversely, those who remain in passenger cars for the trip are considered to be in danger of car fires from electrical mishaps.

The absence of fatalities in the Channel Tunnel fire, when compared with fires at Mont Blanc (linking France and Italy), Tauern (linking Austria and Italy), and Kaprun (in Austria), have been attributed to the Channel Tunnel's being a three-tube tunnel while the others are single-bore tunnels. With multi-tube tunnels, the non-incident tubes can be used to shuttle equipment and staff to the accident site; this emergency response pattern does not exist in single-bore tunnels. But both the geography of a tunnel's location and the construction costs play a role in the decision of whether to construct a single- or multi-bore tunnel. At the time it was built, the Channel Tunnel was the most expensive construction project planned, and it eventually cost more than $21 billion to complete. The time from start to completion (1988 to

1994) and the costs may preclude similar construction of multi-bore tunnels in all but a few locations.

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3.2.8 Subway Sarin Gas Attack

Location:	Tokyo, Japan
Date:	March 20, 1995
Incident Category:	gas attack
Tunnel Length:	N/A; attacks were in the subway
Fatalities and Injuries:	12 fatalities, 5,000 to 6,000 exposed to chemical gas

Synopsis

The Aum Shinrikyo religious sect released five canisters of diluted sarin, an extremely toxic chemical, disguised in lunch boxes and soft drink containers on five separate trains during the Tokyo subway system's morning rush hour. Twelve people died, and between 5,000 and 6,000 people may have been exposed to the chemical.

Analysis of Pre-Incident Information and Events

Aum Shinrikyo was unknown to the public, especially outside Japan, until the March 20, 1995, attack. The leader of the group, Shoko Ashara, was a half-blind former acupuncturist who had turned to religion and mysticism. Born in 1955, he was known as Chizue Matsumoto before he changed his name. In 1984, he founded the Aum Shinsen Club and recruited 15 followers. Membership swelled into the tens of thousands in Japan, in the Soviet Union, and then in Russia and the newly independent republics that had been part of the Soviet Union. Around 1987, the group changed its name to Aum Shinrikyo, which means "supreme truth," and members began to view Ashara as their god. At its peak, the group was believed to have had close to 40,000 members in six countries.

Ashara developed the group's primary aim of overthrowing the Japanese government. The group experimented with a range of chemical agents, including variants of nerve agents, such as sarin, tabun, soman, and VX. The group also explored using hydrogen cyanide, phosgene, and mustard agents. The group was believed to have settled on sarin primarily because it is relatively easy to manufacture. Group members working in Kamikuishiki, Japan, made the gas used in the attacks.

Group members made several attempts to use chemical weapons before their attacks on the subway system, initially targeting rival religious and cult leaders. On July 27, 1994, Aum Shinrikyo released sarin gas using a truck-mounted dispersal system located outside an apartment complex at Matsumoto, a city about 93 miles (150 kilometers) northwest of Tokyo. The gas traveled through the open windows into the building, where occupants were sleeping. Seven people died, and 600 were sickened by the attack, which was intended to assassinate judges who were expected to decide a land dispute that would have been injurious to group members.

Despite a massive investigation, police were unable to trace the chemical agent to the group. Police later learned that the group had tested sarin on animals in Australia and had used the Matsumoto attack to further test weapons. The police were still investigating Aum Shinrikyo at the time of the subway attacks.

Analysis of the Incident

The attack occurred at the height of rush hour and used approximately 1.9 gallons (7 liters) of high-grade sarin. Occurring on a Monday morning on one of the world's busiest commuter transport systems, the attack was intended to affect hundreds of thousands of people and garner worldwide attention. Millions of people are transported on Tokyo's subway; during rush hours, the trains are often so crowded that it is virtually impossible for passengers to move.

Ten male group members, working in two-man teams, were able to release sarin on five different subway lines that merged at the Kasumigaseki station, which is the closest station to the Tokyo police headquarters. Five of the group members released the gas, while the other five served as getaway drivers. The sarin was packaged in plastic bags and was activated when each bag was punctured with an umbrella.

Sarin packets were dropped on the Chiyoda line by a group member wearing a surgical mask typically worn on cold days. He punctured his bag of sarin at a station in the central business district, killing two people and seriously injuring 231. The second sarin packet was released on the Marunouchi line. Despite passengers being removed from the train, the train continued to another station with the third car soaked with sarin. New passengers boarded the train and were affected until the train was taken out of service. One person died, and 358 were seriously injured. The third release, also on the Marunouchi line, was less successful, but when the train reached its destination at 8:30 a.m., searchers evacuated it but failed to find the sarin packets and allowed the train to remain in service. The train was not taken out of service until 9:27 a.m. In the fourth attack, a group member boarded the first car of the 7:59 a.m. train on the Hibiya line. Three stops after he punctured his packets, passengers began to panic. Although some passengers were removed and taken to the hospital, the train continued in service with the empty first car. One person died, and 532 were seriously injured.

In the last attack, also on the Hibiya line, the group member boarded the third car of the 7:43 a.m. train and released his three packets of sarin (all other attackers had only one packet each) two stops later. It is possible that passengers were affected immediately because he released more sarin than the others did. At the next station, a passenger kicked the sarin onto the platform, resulting in four deaths at the station. Sarin remained on the train, which continued on its route until a passenger pressed the emergency stop button at 8:10 a.m. Because the train was in a tunnel, it proceeded to the next stop. When the doors were opened, several people collapsed and the train was taken out of service. The train made five stops after the sarin was released, killing eight people and seriously injuring 275.

Although all the actions surrounding the attack took place on the subways, the group members had hoped that releasing the gas on these particular trains would cause deaths in police headquarters and other government buildings in the immediate area.

Fatalities and Injuries

Victims left the trains and staggered onto platforms, vomiting and foaming at the mouth. Hundreds were dazed and blinded by the gas. In addition to the fatalities on the specific train lines, people affected by the sarin had a variety of respiratory problems. They also suffered convulsions, paralysis, uncontrollable trembling, and high fevers.

Sarin is an extremely deadly gas. The small number of deaths (twelve) was attributed to the chemical being heavily diluted. Two people died immediately after admission to the hospital; the last death related to the incident occurred on June 12, 1996, when a 52-year-old victim died in a Tokyo hospital.

Long-term disabilities have continued to affect many of the injured, who report suffering disturbed sleep and nightmares, sensitivity to light and other vision problems, loss of memory, and post-traumatic stress disorder, for which many are expected to be treated for the rest of their lives. Others suffered permanent mental retardation and loss of motor control.

Fire and Emergency Response

Among the dozen victims of the attack, several were subway employees who tried to save others by removing the sarin bags and were poisoned during their efforts. One of the victims was an employee of the Teito Rapid Transit Authority who was working at one of the stations that the trains passed through. Despite these efforts, the incident exposed a lack of coordination among Japan's police departments and other authorities that was similar to the problems that have become common at major disaster sites.

Despite the efforts of individual employees, all emergency responders, including police, fire, and ambulance services, were criticized for the handling of the sarin attacks. The subway authority was severely criticized for failing to halt trains despite reports of injured passengers. Some hospitals turned away victims, and one was censured for failing to admit a victim for almost an hour. The media were criticized because some who were reporting the story hesitated when asked to transport victims to the hospital. Some of the confusion was attributed to lack of knowledge about sarin poisoning.

Criminal Justice System Response

Because the crime was premeditated rather than accidental, the police response was a large part of the incident aftermath. The police raided Aum Shinrikyo locations and seized a large amount of chemicals normally used in the manufacture of sarin and mustard gases, VX, and other biological agents. There was also evidence that group members had been attempting to manufacture assault rifles based on the design of the Russian-made AK-47.

Between the time Japanese authorities learned of Aum Shinrikyo and late 2004, more than 400 members of the group were arrested. About 100 have been convicted of crimes, including attempted murder, kidnapping, wiretapping, and possession of illegal weapons. On February 27, 2004, Shoko Asahara was found guilty and was sentenced to death by the presiding judge in Tokyo District Court. Forty-eight years old when sentenced, Asahara, whose trial began in 1996, was found guilty of 13 charges, one each for the 12 deaths that occurred and one additional charge. He was the twelfth member of the group to be sentenced to death. Throughout the trial he refused to answer questions and made only confusing statements about the incident. On May 28, 2004, another group member, who had originally escaped the death penalty, had his life sentence changed to the death penalty by a judge who ruled that the group member's role as a coordinator of the attack made him as guilty as those who had actually released the gas in the subway system. The group member's appeal to the Supreme Court of Japan is expected to take years to resolve.

The group was forced to release its property to pay victims' claims. This forced release of property was one reason for the group's diminished membership and name change. Despite attempts to force the group to disband under a 1952 anti-subversion law originally passed to outlaw communist groups, a government commission ruled in 1997 that Aum Shinrikyo no longer presented a threat to the public. After parliament passed a law in December 1999 permitting close police scrutiny of organizations that had committed mass murder, the group changed its name to Aleph. Aleph claims to have renounced violence and is primarily involved in yoga and meditation. It also maintains a website to publicize it beliefs.

Damage and Service Restoration

Although Aum Shinrikyo had enough sarin to kill 4.2 million people, only 12 people were killed in the attacks. The efficiency of the air filtering systems in the subway network was credited with keeping the number of fatalities low.

The subway system has permanently removed garbage cans to prevent terrorists from placing bombs or nerve gas canisters there, but few other security measures have been undertaken by the transit system or in government buildings.

The attack occurred less than 3 months after the Kobe earthquake; many economists thought the two events would have a serious negative effect on what had been seen as a rising economy. The two events also led to emotional questioning within the country, because many of the leaders of Aum Shinrikyo had attended top universities and were viewed as elite members of a society in which status and position are difficult to achieve.

Conclusions

Government studies of the incident found that the response to the disaster lacked coordination. A major reason for this lack of coordination was the vertical structure of Japan's society, where each agency that responded (police, fire, hospitals, and other governmental units) acted independently under its own chain of command. This finding led to the formation of a Severe Chemical Hazard Response Team to preclude a lack of coordination and to encourage information sharing.

Because the attacks were unique in their use of lethal gas, many of the post-analyses have focused on medical response to the incident. Typical sarin poisoning symptoms are convulsions, vomiting, loss of balance, double vision, and slurred speech. Hospitals treated the victims with drug inhibitors and antidotes, primarily atropine and two-pan chloride. The drugs were found to be in short supply, and only the most severe cases could be treated with the antidote serum.

A review of the incident response also determined that decontamination procedures were lacking. Of the 1,364 emergency medical technicians dispatched to the incident, 135 were secondarily affected. Twenty-three percent of the medical staff at the hospitals where the injured were transported later complained of symptoms and signs of secondary exposure.

The incident highlights the potential for creating mass terror by an attack in a public transit system. The ease with which the sarin was released and the problems isolating the sarin, halting train movements, and handling large numbers of injured and hysterical patrons cannot be easily dismissed. A transit system can never fully prepare for such incidents. Current efforts to create and place sensors to recognize chemical or biological weaponry may prevent some attacks, but the terrorists will always seek to devise new ways of bypassing sensors or using chemicals not yet detectable.

Since the sarin gas attack, more cities with mass transit systems have become involved in cross-agency and cross-jurisdictional pre-incident planning and training. In addition, transit agencies have become more receptive to placing anti-tampering devices on their ventilation systems; closing off open, nonpublic areas or public areas during nonpeak periods; formalizing policies and procedures for stopping trains and taking them out of service; and launching passenger education and awareness campaigns to help recognize suspicious items or behaviors. Although these precautionary efforts are worthwhile, it is unlikely that any of the awareness campaigns would have prevented the sarin attacks on March 20, 1995.

The attacks continue to have political repercussions in Japan. Pointing to the large financial payouts Americans received after the September 11, 2001, attacks, protestors have argued that the Japanese government should pay a larger price for not having taken the threat of Aum Shinrikyo seriously enough. Taking the threat seriously enough might have resulted in actions that would have prevented the sarin attacks.

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3.2.9 Chicago Freight Tunnel Flood

Location:	Chicago, Illinois
Date:	April 13, 1992
Incident Category:	flood in unused, underwater, and underground freight tunnel
Tunnel Length:	50 miles (80 kilometers)
Fatalities and Injuries:	0 fatalities, 0 injuries

Synopsis

A piling driven into the Chicago River bottom caused a leak in the underground freight tunnel. The inrush of water spread through much of the system's 50 miles (80 kilometers) of tunnels. Although there were no deaths or significant injuries, the disruption caused flooding to more than 50 buildings, most of which had to be evacuated. The disruption flooded stores and halted utility service throughout Chicago's Downtown Loop area. More than 250,000 people were evacuated from some of Chicago's busiest and most famous buildings, including the Sears Tower, the Merchandise Mart, and Marshall Field's Department Store. Declared a local, state, and federal emergency, the flood was estimated to have cost Chicago $40 million for the five and a half weeks it took to pump the water from the tunnel and as much as $2 billion in lost revenue, tax assessment losses, and damage to the city's infrastructure.

Analysis of Pre-Incident Information and Events

The Chicago freight tunnel system was constructed between 1899 and 1904, originally for a telephone system that was never created. The tunnel system was used to deliver coal, remove ash, and deliver freight directly by railroad transfer or by trucks that delivered merchandise at street level. The merchandise was then transported on rail cars for unloading at specific stores' underground sidings. A 2-foot-gauge, mine-type electric railway operated in the tunnels, connecting to major railroad and port facilities. Over the years, the 62 miles (100 kilometers) of tunnel had shrunk to about 50 miles (80 kilometers) because of construction by the Chicago Transit Authority (CTA) of the State Street subway, the Dearborn Street subway, and the Kennedy Expressway. At the time of the flood, the tunnel ran under many important buildings in downtown Chicago and criss-crossed under the Chicago River at a dozen locations.

Although the tunnel system was unknown to most residents after it was abandoned in 1959, it was equipped with a 24-inch (61-centimeter)-gauge track on which at least one engine and four cars that hauled ash remained intact at the time of the flood. At the time of the flood, telephone companies, cable television companies, and light and power companies (e.g., Commonwealth Edison and Peoples Gas) rented tunnel space from the city to run lines and store equipment. Because the responsibility for the tunnels had been transferred among a variety of city agencies over time, the existence of the tunnels had been virtually forgotten and little oversight was exercised.

Some of the tunnel system's statistics give an indication of its size and complexity. When described in 1928 (considered accurate at the time of the flood), the tunnel, which measured 6 by 7.5 feet (1.8 by 2.3 meters), encompassed 734 intersections and sidings, had 96 elevators (not all operable), 266 telephones that once connected to the Chicago Tunnel Company's central station dispatchers, 540 pumps, 63 sumps, and almost 4,000 lights. The average distance of the tunnel below street level was 40 feet (12 meters).

Providing an indication of its importance to early commerce, there were 26 private merchandise connections for freight delivery, 40 connections for picking up and delivering coal and cinder, 16 connections for cinder only, three coal receiving stations, and four universal public stations. At the public stations, anyone could have dropped a shipment to be routed through the tunnels via any of the 49 railroad connections.

Analysis of the Incident

At about 5:30 a.m. on April 13, a slow leak that had probably been in existence for the previous 7 months began to flood the tunnel system. The flood was discovered by a boiler room engineer working at the Merchandise Mart, north of the Loop, who heard the sound of running water. He was located in the lowest basement of the Mart, about 30 feet (9 meters) below the level where the Chicago River was flooding into the tunnel. The Chicago fire department was notified at 5:57 a.m. Shortly after 6:00 a.m., the Chicago Emergency Preparedness and Disaster Service, part of the fire department, activated the city's emergency operation plan and sought to locate the source of the water, which was initially thought to be a sewer or water main that had burst.

By 6:30 a.m., after a citizen reported seeing a whirlpool in the Chicago River's North Branch near the Kinzie Street bridge, it was determined that the source of the water was a hole in the tunnel near the bridge. The hole was later determined to have been caused by a bridge piling that had been inadvertently pounded into the side of the tunnel exactly where the whirlpool was observed.

Between 7:00 and 8:00 a.m., flooding was reported in five more buildings, including Marshall Field's Department Store. By 9:00 a.m., 11 feet (3.3 meters) of water had filled the lowest of City's Hall's three basement levels. Shortly thereafter, City Hall was evacuated, power was shut down by Commonwealth Edison, and additional buildings were evacuated. At about 9:00 a.m., water was discovered in the subway tunnels and the CTA stopped all service. At 11:00 a.m., the entire downtown Loop area, from the Chicago River south to Taylor Street and from Canal Street east to Michigan Avenue, was shut down. The evacuation involved about 250,000 people.

By noon, 23 buildings had been flooded. Although quick-dry concrete had been poured into the area around the hole by Kenny Construction Company, a private firm employed by the city, about 250 million gallons (946 million liters) of water, containing fish and debris from the river, continued to flood the basements of more than 50 buildings in the Loop.

Fatalities and Injuries

There were no fatalities and no injuries reported as a result of the incident.

Fire and Emergency Response

The Chicago fire department was notified at 5:57 a.m., less than a half hour after the leak was observed. Shortly after 6:00 a.m., the Chicago Emergency Preparedness and Disaster Service, a part of the fire department, activated the city's emergency operations plan. Despite this effort, the source of the water, initially thought to be a sewer or water main break, was discovered inadvertently to be the Chicago River leaking into the old Chicago freight tunnel.

By early the first day of the incident, the Illinois Emergency Management Agency (IEMA) and the American Red Cross were involved. Both Chicago Mayor Richard M. Daley and Illinois Governor Jim Edgar declared emergencies, and a joint command center was established for all emergency workers near the breach site. On the evening of April 14 (the second day of the incident), Mayor Daley contacted the White House to request assistance from FEMA. The request was approved and received the following day. Despite disputes between the city and the state over financial responsibilities, on April 18 (five days after the incident), the U.S. Army Corps of Engineers was assigned to seal the breach in the tunnel and then to remove the accumulated water from the freight tunnel system and other affected areas.

The dewatering process continued until May 22; work associated with sealing the tunnel continued until June 30, 1992.

Damage and Service Restoration

Although service was restored within 3 days, it took five and a half weeks to pump water out of the tunnel system at a cost of $40 million. It took additional months for the Loop area to return to its previous state. The cost in lost business was estimated at almost $2 billion. Nine employees of the city of Chicago, including the acting transportation commissioner, lost their jobs after it was determined that they had ignored reports months earlier that the tunnel was leaking. At that time, about 7 months before the flood, the estimated cost of repairing the leak had been less than $10,000.

Illinois Bell activated and maintained its 24-hour emergency operations center from the first day of the flood until the 31st day (May 13). Call volume on the first day was estimated at about 150,000 per hour, three times the usual volume. Increased volume was also recorded for days in directory assistance calls and requests for call forwarding. Cables were submerged, and fiber optic equipment had to be replaced. Electrical power was restored to about half the buildings in the Loop on April 17.

Beginning the day of the flood, small boats were barred from passing through the Kinzie Street bridge area of the Chicago River. While some traffic was permitted use of the area on April 30, the river was not completely reopened until May 21.

On April 18, the Kennedy Expressway, used by about 200,000 vehicles per day, was closed for fear that it would flood. It remained closed for 10 days, which impacted the transportation system, particularly in light of the continuing subway closures.

The two affected CTA subway lines also incurred costs and service delays. The State Street subway did not reopen until May 1 (the 19th day). On May 7 (the 25th day), the Dearborn Street subway reopened.

Conclusions

Subsequent to the incident, it was learned that the flood might have been prevented had the initial crack in the tunnel under the Chicago River been repaired for less than $10,000. This crack had been reported to at least one city agency by the company that installed the pilings, but the report was ignored. Forty million dollars was spent on pumping and plugging the leak, and an estimated $2 billion was spent on overall costs of the incident.

The structural stability of many buildings had to be ensured; there were numerous safety issues involving asbestos and polychlorinated biphenyls (PCBs) in water-damaged buildings. Insurance coverage, evacuation plans, and safe storage of business records were affected.

Among the recommendations to mitigate similar hazards were surveying the freight tunnel system, including documentation of conditions and locations of access shafts, bulkheads, floodgates, building closures, and utilities; preparing a comprehensive map of Chicago's underground infrastructure; and surveying all buildings with subbasements adjacent to the tunnel system. This last effort was intended to chart the existence of bulkheads and test their effectiveness in preventing a similar incident.

Other recommendations pertained to correcting existing installations of flood monitoring equipment, providing uniform specifications for bulkhead and floodgate designs for all buildings with subbasements adjacent to the tunnel, and encouraging individual buildings to either assign space for utilities above the flood level or require water-tight splices for below-flood-level telephone cables.

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3.2.10 London Underground (the Tube) King's Cross Station Fire

Location:	London, England
Date:	November 18, 1987
Incident Category:	fire in escalator in Tube station
Tunnel Length:	N/A; Tube station
Fatalities and Injuries:	31 fatalities, injuries not tallied

Synopsis

A fire that started in one of four escalators in the London Underground King's Cross station, one of the busiest stations in the system, spread throughout the station and into a ticket hall at about 7:30 p.m., at the end of the evening rush hour. The draft created by train movements, the steep incline of both the escalator and the station itself, and the old paint on the ticket hall walls contributed to create a fast-moving inferno that engulfed the station and thousands of patrons, resulting in 31 deaths.

Analysis of Pre-Incident Information and Events

At the time of the incident, King's Cross was the busiest station in the London Underground system. Five lines (the Metropolitan, Circle, Piccadilly, Northern, and Victoria) operated on four different levels. The station was built on five levels, including passageways, shafts, and tunnels, and during its busiest rush hours, 2,000 passengers per minute moved through the station. The station has been described as a labyrinth of passageways, shafts, and tunnels, including the subway, which connected the Piccadilly and Victoria platforms to the Midland City station. This connection was closed off with locked gates when the incident began.

The escalators where the fire began were installed in 1939, and there had been a history of fires occurring in their mechanisms. Because of this history, the escalators had been fitted with water fog equipment, which basically consisted of water sprays that were located under each escalator and manually operated by valves on a landing inside the access door to the upper machine room. Three access staircases were also located in the area—one between Escalators 4 and 5, another between Escalators 5 and 6, and a third under Escalator 5.

Analysis of the Incident

The incident began at 7:29 p.m., when a fire was reported by a passenger coming up Piccadilly Line Escalator 4 (one of four escalators in the station). The passenger noticed the fire one-third to halfway up the escalator and informed a ticket office clerk, who telephoned the station inspector on the Victoria Line platform. Within a minute, another passenger who had come up the same escalator pressed the stop button and shouted a warning to passengers to disembark the escalator. A British Transport Police (BTP) officer in the ticket hall's control room heard the commotion and responded to the incident.

Although the fire above the escalator seemed small, the BTP officer determined that there might be a more serious fire under the escalator. At 7:33 p.m., he left the scene to go above ground to advise the BTP control room of the fire. He left because his portable radio was inoperable underground. The London Fire Brigade was alerted to the fire by the BTP control room at 7:34 p.m., and fire units were dispatched 2 minutes later. The fire was still small, described in size as similar to a fire created by a large, burning cardboard box. However, by 7:45 p.m., the fire had spread rapidly to the ticket hall at the top of the escalators, where it quickly turned into an inferno that destroyed the ticket hall. All but one of the deaths occurred in the period immediately following the spread of the fire.

Fatalities and Injuries

Thirty-one people, including one BTP employee, were killed. There were a large number of serious injuries. One of the victims remained unknown until January 2004, when 72-year-old Alexander Fallon, of Scotland, was identified through forensic evidence.

Fire and Emergency Response

Before the fire units arrived at 7:42 p.m., the Piccadilly Line escalator had been stopped and taped off by BTP employees and officers who had arrived in response to the initial officer's radio message to central control. They directed passengers from the Northern and Piccadilly Lines via the cross passage up the Victoria Line escalator. People entering the station were directed down the Victoria Line escalator. At about 7:40 p.m., just prior to arrival of the fire brigade, police decided to evacuate the station and to request that trains no longer be allowed to stop at King's Cross. Until then, some passengers and Underground staff had been evacuated by train, and trains continued to run through the station, stopping to discharge passengers.

When the fire units arrived, the fire at Escalator 6 was still small. Firefighters at the top of Escalator 4 thought it was a more significant fire, but not one that would rapidly engulf the entire area. Yet by 7:45 p.m., the fire spread quickly and with great velocity up the escalator and into the ticket hall and surrounding subways, preceded or accompanied by thick black smoke. Despite the size and speed of the fire, the incident ended quickly. The fire was deemed under control by 9:48 p.m.

Damage and Service Restoration

Since service was restored to King's Cross station, work on the facility has been almost constant. Total renovation is scheduled for completion in 2007, including extensions and refurbishments that are not directly related to the fire, but are rather in response to changing travel patterns and what is expected to be an increase to 82,000 passengers using the station during the morning rush hour.

Conclusions

The King's Cross fire was only the third incident investigated under the 1871 Railway Act; the previous two incidents were the Tay Bridge disaster in 1879 and the Hixton Level Crossing accident in 1968. A formal investigation, announced on November 25 by the Secretary of State for Transport, was headed by Desmond Fennell. His final report led to legislative initiatives to include fire safety standards for underground railway stations under Section 12 of the Fire Precautions Act, which at the time applied only to offices, shops, factories, and hotels.

The absence of interoperable communications played a role in both the fire and the emergency response. The first police officer at the scene was forced to leave to communicate with central control because of the inoperability of his radio underground. Train service might have been curtailed earlier had there been more explicit communications between BTP and the fire units. People trapped during the fire were in telephone communications with BTP line controllers, the headquarters central controllers, and the BTP controllers, but there was no direct communication with those fighting the fire on the surface, who remained unaware of the people trapped in the station.

The situation was exacerbated by the firefighters' lack of knowledge of the station. Two examples of this occurred when, at 8:17 p.m., two BTP officers evacuated an injured passenger via the Midland City subway, but did not communicate with the firefighters, who were unaware of the existence of that subway. At 9:05 p.m., the BTP incident officers arrived via the Midland City subway and went above ground to meet with the fire officer in command, but they did not inform the fire officer that they had arrived via subway. Firefighters were finally dispatched underground via the Midland City subway at 9:15 p.m., an hour and a half after the fire began and only about half an hour after the fire was declared under control.

Simulations of the flow of gases following the fire concluded that a trench effect was responsible for the rapid spread of the fire; this conclusion contradicted the original theory that the rapid spread was due to train movements. The fire started about 70 feet (21 meters) from the top of Escalator 4, although there was also damage to Escalators 5 and 6.

The rapid spread of the fire when it reached the ticket hall was later attributed less to the draft created by train movements than to factors in the hall. The floor area of the ticket hall, excluding the ticket office, was approximately 5,700 square feet (530 square meters); the height from the floor to the suspended ceiling was 8 feet (2.5 meters). The 138-foot (42-meter) length, the small 23-foot (7-meter) internal diameter, and the steep angle (30 degrees) of the escalator also contributed to the intensity of the fire. The inferno created in the hall was caused by the suspended ceiling, which had been constructed from fire-resistant panels containing asbestos. Many panels fell during the fire, allowing flames to penetrate and burn any combustible materials, including electrical wiring. In addition, wooden and aluminum-based components were burned and charred, resulting in fumes and hot gases that spread through the stairways and tunnel system. The layers of old paint, many of which predated rules pertaining to fire resistance, also contributed to the speed with which the ticket hall was engulfed in flames.

The Fennel Report, which included 157 recommendations that were accepted by London Underground and other organizations involved in underground system emergency oversight and response, highlighted the lack of staff training, cuts in expenditures on cleaning, and the absence of a program to replace the wooden escalators. It specifically mentioned a lack of concern about station maintenance and hygiene. This lack of concern led to acceptance of debris and refuse, including cigarette butts, collecting at the base of the escalators. It was also policy not to contact the fire brigade unless a fire appeared serious; this policy resulted in a work culture where small fires were treated casually by Underground staff.

Despite the number of fatalities and injuries, the public location of the fire and the large number of evacuees resulted in many more eyewitness accounts than usual in tunnel and/or transportation facility incidents. The Fennel Report heard evidence from many eyewitnesses and compared their statements to the logs of the control centers of the fire brigade and the BTP. This effort created a rare qualitative description of the events to compare with the official chronology, which raised questions about the value of such accounts in situations where visibility is low and the level of panic is extremely high.

The Fennel Report led to passage of the Sub-Surface Railway Stations Regulations of 1989 (referred to as "the Regulations" because they were actually introduced under Section 12 of the 1971 Fire Precautions Act). The Regulations mandated replacement of all wooden escalators on the Underground system, installation of automatic sprinklers and heat detectors in escalators, fire safety training for all station staff twice a year, and improvements in communications and liaison among agencies expected to respond to any Underground emergency. The scope of the requirements meant that full compliance with the safety changes was not expected until late 2004, and requirements for safer station exits was not anticipated to be met until 2007. In 2004, a move in Parliament to repeal some of the requirements through the proposed Regulatory Reform (Fire Safety) Order 2004 passed. However, support for the regulations by unions and rider advocacy groups resulted in the House of Commons' Regulatory Reform Committee recommending in October 2004 that both the 1989 and 1971 laws remain in effect.

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3.2.11 Bay Area Rapid Transit (BART) Transbay Tunnel Fire

Location:	San Francisco, California
Date:	January 17, 1979
Incident Category:	fire
Tunnel Length:	3.7-mile (5.9-kilometer) twin-bore tunnel with service tunnel
Fatalities and Injuries:	1 fatality, 58 injuries (including 19 firefighters)

Synopsis

During the evening rush hour on Wednesday, January 17, 1979, a fire broke out in a circuit breaker in the fifth and sixth cars of a seven-car westbound BART train about two miles (3.2 kilometers) into the Transbay Tunnel. The train was stopped by the emergency brake and could not be restarted. An unsuccessful attempt to disconnect the burning cars delayed the evacuation of passengers by about 30 minutes, during which the tunnel filled with smoke despite activation of the ventilation system. Rescue efforts involved taking the passengers out through the service tunnel, although smoke entered both the service and the other main tunnel.

Analysis of Pre-Incident Information and Events

BART is a rapid transit district serving the San Francisco Bay area that includes mainline rail service between San Francisco and Oakland via the two-bore Transbay Tunnel tube. The tube sections resemble huge binoculars in cross section, 24 feet (7.3 meters) high and 48 feet (14.6 meters) wide, with trackways in each bore to carry trains in each direction, and separated by an enclosed central corridor called the gallery. The gallery is divided into two chambers; the lower one serves for pedestrian and maintenance access as well as for distribution of various electrical and safety systems, and the topmost chamber serves as an air duct for the ventilation system pioneered by BART.

BART officials were optimistic about the ventilation system's design and ability to safely handle a fire under the Bay, but San Francisco's assistant fire chief had voiced concern that fighting a fire in the tunnel would be like entering a 3-mile (4.8-kilometer)-long high-rise building that was lying on its side and had no windows. Everyone had agreed that smoke would be the major problem should a fire occur; they were all correct.

A few hours prior to the incident, at 4:45 p.m. on January 17, a westbound train had stalled in the tunnel for about 20 minutes. Passengers later reported that there had been sparks, explosion-like sounds, and flashes that seemed to warn of a fire. Even closer to the time of the incident, at 5:15 p.m., patrons at the Embarcadero station on the San Francisco side of the tunnel reported seeing smoke coming from the west side of the tunnel. Problems prior to the stalling of the 6:06 p.m. train that caught fire were acknowledged by BART, but the system officials said there did not appear to be any connection between the earlier reports and the incident that closed the tunnel.

Analysis of the Incident

On January 17, 1979, at about 6:00 p.m., a fire occurred in the fifth and sixth cars of a seven-car train (Train No. 117) traveling from Oakland to San Francisco in the Transbay Tunnel Tube Bore A. The train was stopped, passengers were moved into the forward cars to avoid the fire, and the exhaust fans in both vents located at each end of the tube were activated to draw the smoke out of the tunnel tube.

The last cars of the train were uncoupled from the train, but attempts to move the rest of the train were unsuccessful. The NTSB later determined that the uncoupling system malfunctioned because of a short in the train's control circuit. At the same time, personnel from BART and from both the Oakland and San Francisco fire departments entered the tunnel to rescue staff and passengers.

There were numerous miscommunications almost as soon as the incident began. San Francisco fire department tapes showed a call from BART dispatchers at 6:00 p.m., but the dispatchers stated that they had reached a wrong number and were disconnected. At 6:09 p.m., BART contacted the Oakland fire department, which dispatched one unit of about 10 firefighters. These firefighters proceeded to the Oakland West station to board a special train, while a second unit of firefighters entered the tunnel walkway on foot. The San Francisco fire department was not officially contacted until 6:34 p.m., 25 minutes after Oakland was notified and 34 minutes after the first call made to the department was disconnected.

Indecision about the rescue train led to BART dispatching an eastbound train filled with rush-hour passengers to act as the rescue vehicle. The decision to send a train with passengers from the Embarcadero station was based on the view that it would have taken at least 10 minutes to order the approximately 1,000 passengers off the train. When the train stopped in the tunnel to pick up the passengers stranded from the disabled train, passengers in the rescue train were told only that they would be stopping for other passengers but were not told that there was a fire in the other tunnel tube. The rescue train remained in the adjacent tube for about 45 minutes, during which there were no lights or fresh air on that train, and some passengers smelled smoke coming from the other tunnel.

Intense smoke minimized visibility and hampered rescue efforts. It was later found to contain toxic materials attributed to combustion of the train's polyurethane seats. The material had previously been identified as a potential fire hazard; BART had received a $2.5 million federal grant for replacement with less flammable materials. At the time of the incident, BART was preparing to secure bids for replacement seats and had estimated that it would take at least a year for new seats to be obtained and installed.

The fire was declared under control at about 10:45 p.m., although it took more time for the fires in the rear-end cars to be fully extinguished. They were then pulled from the tunnel by a diesel engine. Their windows and roofs were missing, and they were described as crumpled like pieces of tin foil. About 24 hours after the original incident, Oakland firefighters arrived at BART's storage yard to douse a small fire that flared in the gutted train.

Fatalities and Injuries

The single fatality (Oakland firefighter William Elliott, 50, who died of a combination of smoke inhalation and flue gas poisoning) and the injuries to passengers and firefighters were caused primarily by gases from the combustion of plastics.

Fire and Emergency Response

Fire personnel from the San Francisco and Oakland fire departments responded to the incident, which occurred about a mile (1.6 kilometers) from the Oakland end of the tunnel tube. The fire started small and was originally recorded by the Oakland fire department as a two-alarm fire. Although the tunnel's ventilation system was working, it did not expel smoke quickly enough and allowed smoke to fill the tunnel. The dense smoke limited visibility to almost zero and impeded rescue efforts; it took almost 40 minutes for Oakland firefighters to reach the train. By that time, passengers, many of whom had panicked, had crawled along the train's floor in an effort to escape the fire by entering the more forward cars.

Once firefighters were able to reach the passengers, the passengers were removed via a narrow trackside catwalk through emergency doors to the gallery ways between the eastbound and westbound tunnel tubes and onto an eastbound train that took them to the West Oakland station. Paramedics treated many people at the scene, where ambulances waited to take the more seriously injured to hospitals.

Of the injured people, 24 passengers, 19 firefighters, and three BART employees were sent to three Oakland hospitals and one San Francisco hospital. Most, with the exception of the firefighter who died, were treated for smoke inhalation and noncritical injuries. Because of the thick smoke and the time it took firefighters to reach the wreck, a number of the firefighters reported running out of oxygen. Despite the heavy smoke, a few of them were able to make it completely through the tunnel. Some of the Oakland firefighters walked the entire length of the tube and emerged at the San Francisco end; they were among the seven firefighters taken to San Francisco General Hospital.

Damage and Service Restoration

Damage to the gutted BART cars was estimated at $800,000. No other monetary damage figures were publicized.

Although BART intended to restore service within days of the incident, criticism by California Public Utilities Commission (PUC) investigators and Oakland and San Francisco fire officials prevented this from occurring. The fire departments criticized BART officials for not giving firefighters what they called "ultimate authority" during the incident. San Francisco's fire chief announced that his department was planning to conduct its own investigation of events surrounding the fire.

BART had been running test trains through the fire-damaged tunnel prior to the meeting of the PUC. However, within 3 days of the incident, the PUC ordered BART to keep the Transbay Tunnel closed until a number of safety improvement actions had been taken, including the following:

- Present sworn testimony that both tunnels were structurally sound and operationally safe, and have the testimony verified by either Caltrans or the California Department of Industrial Safety.
- Develop a plan to keep smoke from a burning train out of the gallery that separates the two tunnel tubes.

- Provide appropriate rescue equipment (e.g., emergency vehicles, golf carts for moving in the walkway, and breathing apparatuses for emergency responders) and improved communications.
- Revise rescue procedures so that the fire chief of either Oakland or San Francisco, depending solely on where the fire occurred, was in charge of operations.
- Change the doors to the gallery to enable people inside to get out as easily as people outside to get in.
- Receive approval from the Oakland and San Francisco fire chiefs on the new fire rescue procedures.

Conclusions

Both fire departments had practiced tunnel emergency procedures in drills that involved entering the tunnel tubes and the central corridor, or the gallery that connects them. Firefighters were trained that the gallery was the place to flee to during a fire or smoke condition because panic doors every 100 feet (30 meters) were programmed to open as soon as they were touched. Although this worked during drills, in the actual incident the gallery filled with smoke, thus becoming a dangerous location. When firefighters tried to exit the gallery and enter the relative safety of the eastbound (unaffected) tube, they were unable to find the keyholes in the doors. The firefighter who died was trapped in the smoke-filled gallery.

The incident was attributed to lack of communication between the train operator and central operations, poor coordination, and errors of judgment, all of which made the incident a key factor in the development of National Fire Protection Association transit industry guidelines (NFPA 130) on responses to fire incidents [Ref. 2].

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3.2.12 Port Authority Trans-Hudson (PATH) Evacuation under the World Trade Center

Location:	PATH rapid transit station under the World Trade Center
Date:	September 11, 2001
Incident Category:	terrorist bombing of buildings above the rail station
Tunnel Length:	N/A; rail station under bombed building
Fatalities and Injuries:	None in this portion of the incident

Synopsis

Two planes flown by terrorists struck the World Trade Center’s (WTC’s) twin towers during the morning rush hour on September 11, 2001, resulting in fire and heat that caused the buildings to collapse. This case study does not discuss the overall incident, but looks specifically at the successful evacuation of employees, passengers, and trains from the PATH rapid transit station under the WTC.

Analysis of Pre-Incident Information and Events

PATH was acquired in 1962 by the Port Authority of New York and New Jersey from the bankrupt Hudson and Manhattan Railroad. The system and its tunnels linking New York and New Jersey, which had been built in 1908, were the first passenger rail connections between the two states. Prior to September 11, 2001, the PATH rapid transit system of 13 stations carried approximately 260,000 weekday passengers, about 67,000 of whom boarded PATH at the WTC station located about 70 feet (21 meters) below the WTC towers.

When the first plane hit the WTC at 8:46 a.m., the PATH rush hour was not quite over. Yet within 5 minutes, despite the surrounding chaos, a train dispatcher at the station had the presence of mind to ask his control center what he should do about passengers he had just unloaded and those who had just entered his train on Track 4. He was told to immediately take his train and passengers out of the station and back to New Jersey. Although tapes released later indicated that at least one conductor did not think he would be able to reverse his train to get out of the 14th Street station, passengers at Manhattan stations were boarded or reboarded onto trains that traveled under the Hudson, returning them all to safety in New Jersey.

The only train that was unable to leave the WTC station was found later on Track 4 with debris covering four of its seven cars. However, there were no fatalities because all occupants had fled the station before the buildings collapsed.

Analysis of the Incident

Within minutes of the first plane striking the north tower of the WTC at 8:46 a.m., at least four PATH employees individually contacted the PATH control center at Journal Square in Jersey City to report that an unexplained explosion or fire seemed to have occurred at the WTC. None were aware of the magnitude of the event. Based on instructions from a PATH deputy director who was at the WTC, by 8:52 a.m. the system's trainmaster began to issue instructions to conductors and operators to avoid the station. Had it not been for these prompt instructions, trains would have continued to arrive at the station at 3- and 5-minute intervals, unloading passengers directly into buildings that would soon collapse. This would undoubtedly have resulted in a far larger number of deaths in conjunction with the WTC attack.

Staff aboard a train from Newark that was carrying about 1,000 passengers announced that passengers should reboard; the staff then moved the train out of the station and to the Exchange Place station in Jersey City. The passengers who had not reboarded were evacuated from the Trade Center by Port Authority police officers and other operations personnel. A second train originating in Hoboken, New Jersey, and also carrying approximately 1,000 passengers was scheduled to arrive at the WTC station just after the Newark train. The crew was ordered by the trainmaster to keep its doors closed, move through the WTC, and loop around and proceed to Exchange Place. A third train scheduled to leave the Exchange Place station for the WTC station was directed to discharge all passengers at Exchange Place and to proceed to the WTC to evacuate any stranded passengers and Port Authority personnel. That train, which left the station at about 9:10 a.m., was the last to leave before all city-bound trains were halted in New Jersey. The timely decision to evacuate trains from the WTC station and to halt those heading toward it resulted in no trains being trapped in the tunnels when the towers collapsed and no passengers or staff being left in the station.

Fatalities and Injuries

There were no fatalities or injuries in this portion of the incident.

Fire and Emergency Response

Fire and emergency response was not involved for this portion of the incident.

Damage and Service Restoration

An important part of damage control that pertained specifically to the PATH portion of the events of September 11, 2001, involved securing the basin under the collapsed towers to ensure that the PATH system was not flooded beyond the immediate event. A 60-foot (18-meter)-deep cavern that became known as the "bathtub" formed the foundation and side walls of the basement levels of the WTC and kept out water from the Hudson River. If the bathtub had given way, water would have rushed into what had been the basement levels of the WTC and subsequently into the two PATH tubes under the river. Although some water damage occurred at the Exchange Place station in Jersey City, had the water not been contained it could have reached the PATH terminus at West 33rd Street and Sixth Avenue in midtown Manhattan, and from there flooded adjoining New York City subway tunnels. Further flooding was prevented, and it was eventually determined that much of the water in the PATH tubes was not from the bathtub, but from broken water mains, firefighters' hoses, and rainwater.

On November 23, 2003, PATH service linking lower Manhattan and New Jersey was restored at the temporary WTC PATH station. The station, which opened 1 month ahead of schedule, was the final part of Port Authority's $566 million program to restore the rail service into lower Manhattan that was severed on September 11, 2001. It was the first public space to re-open within the WTC site since the terrorist attacks. Although the temporary station cost $323 million to build, the station lacks many of the amenities of the original station, including heating, air conditioning, and features necessary to comply with the federal Americans with Disabilities Act (ADA). It is planned that these features will be included in the permanent station.

In addition to the cost of the temporary station, $106 million was spent by the Port Authority to restore the PATH tunnels under the Hudson River. The interior of some tunnel sections had to be stripped, and equipment damaged by the collapse of the towers and subsequent flooding (such as tracks, electrical wiring, and train signals) had to be replaced. The $106 million also included restoration and enhancement of the Exchange Place station in Jersey City.

The WTC temporary station is slated to be replaced with a proposed $2 billion permanent WTC Transportation Hub that will include underground pedestrian connections to more than a dozen New York City subway stations and an additional connection to the Metropolitan Transportation Authority's proposed Fulton Street Transit Center.

Conclusions

Based on normal ridership patterns, it is estimated that as many as 3,000 PATH passengers were prevented from detraining directly into the WTC station. The immediate decision to halt trains into New York City prevented these passengers and the trains carrying them from being stranded in the station or rail tunnels.

The ability to bring all passengers to safety, including those who were quite literally right under the twin towers, was attributed to a combination of a culture in which workers are encouraged to think independently and act in an emergency without waiting for authorization from higher levels of management and to an independent communications system that allows dispatchers and train operators to communicate freely. The PATH communication system worked throughout the emergency because it was not located on top of the WTC even though both the WTC and the PATH system are components of the Port Authority of New York and New Jersey.

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3.3 Summary of Case Studies

Table 4 shows the details of each case study at a glance. In total, the case studies represent 10 rail incidents and 2 road incidents, taking place in Asia, Russia, western Europe, Great Britain, and the United States. All intentional violent acts occurred on passenger transit systems:

- Moscow terrorist bombing (2/6/2004),
- Daegu arson fire (2/18/2003), and
- Tokyo chemical attack (3/20/1995).

Passenger transit incidents resulted in the largest numbers of casualties and injuries:

- Moscow terrorist bombing (2/6/2004): 39 fatalities, 100+ injuries;
- Daegu arson fire (2/18/2003): 198 fatalities, 147 injuries, 50+ missing;
- Kitzsteinhorn cable car fire (11/11/2000): 155 fatalities, injuries not tallied;
- Tokyo chemical attack (3/20/1995): 12 fatalities, 6,000 exposed to sarin gas;
- King's Cross Station fire (11/18/1987): 31 fatalities, injuries not tallied; and
- BART Transbay fire (1/17/1979): 1 fatality, 58 injuries.

One incident did not result in fire or explosion: Chicago freight tunnel flood (4/13/1992).

3.4 Conclusions

3.4.1 Pinpointing Vulnerabilities

Passenger transit tunnels and stations present a high potential for large numbers of fatalities and injuries, for worldwide media coverage, and for creating public fear. While some transit tunnel incidents can be characterized as accidents, many are intentional acts in which the initiators of the incident are suicidal or seeking to kill or injure large numbers of people. Even when there is little or no intent to cause chaos or mass casualties, the possibilities for such outcomes are strong.

Road tunnel fires are closely related to truck accidents. These accidents frequently result in fires, and the fires are often exacerbated by the goods being carried. Even when the materials being transported are not flammable or hazardous, serious side effects of fires may be toxic fumes or residue. Freight and motor tunnel incidents hamper economic arrangements by altering patterns for the transport of goods and may lead to long-term damage from flammable cargo or the release of hazardous materials.

3.4.2 Lessons Observed

All the case studies point to a need for better safety management and for better communications. In a number of the incidents, no one person or office was responsible for system safety, sometimes because the organizational culture minimized the importance of working safely and of maintaining a clean and safe system.

There is also a need for better planning of emergency systems and of estimations of overall tunnel usage. Many of the

Table 4. Case study summary.

Section Number	Incident	Date	Fatalities and Injuries	Brief Description
3.2.1	Moscow Subway Suicide Bombing	Feb. 6, 2004	39 fatalities, 100+ injuries	A bomb, later linked to Chechen separatists, exploded inside a crowded Moscow subway train during the morning rush hour. The bomb destroyed the second car of the train as it left the Avtozavodskaya station in southeast Moscow; the train was traveling toward the center of the city. The incident was one of three subway-related bombings attributed to Chechens.
3.2.2	Jungangno (Chungang-Ro) Subway Station Arson Fire	Feb. 18, 2003	198 fatalities, 147 injuries, 50+ missing	A subway passenger threw flammable liquid inside a subway car of a train carrying about 600 people. The liquid ignited as the train pulled into the underground Jungango station, beneath Daegu's central city. A train traveling in the opposite direction entered the tunnel moments after the first train burst into flames. The death toll increased when the doors of the second train locked shut after the driver stopped in the tunnel and removed the master controller key. The passengers were trapped inside as cars filled with smoke and noxious fumes.
3.2.3	St. Gotthard Tunnel Fire	Oct. 24, 2001	11 fatalities, injuries not tallied	A head-on collision of two trucks about 1 mile (1.6 kilometers) from the tunnel's southern entrance sparked an explosion and subsequent fire. Part of the tunnel's roof collapsed over a distance of about 328 feet (100 meters). These two separate events combined to make the 10.6-mile (17-kilometer) tunnel unapproachable due to temperatures as high as 1,832°F (1,000°C) and falling roof debris. Up to 40 cars and trucks were fused into a molten mass at the heart of the disaster zone. The incident resulted in 11 fatalities, including the two truck drivers involved in the accident. Rescue efforts were hampered by the extreme heat and the risk that additional sections of the tunnel roof might collapse.
3.2.4	Howard Street CSX Tunnel Fire	July 18, 2001	0 fatalities, 4 injuries	A 60-car freight train, of which eight cars in the rear half of the train were carrying dangerous or hazardous materials, caught fire, probably due to a derailment in the tunnel. The train was stopped and staff disconnected the locomotives and escaped. There were no fatalities, but the fire resulted in large quantities of smoke escaping the tunnel. The fire brought the city to a halt and resulted in a series of lawsuits by Baltimore against CSX.
3.2.5	Kitzsteinhorn Tunnel Cable Car Fire	Nov. 11, 2000	155 fatalities, injuries not tallied	A cable car packed with skiers caught fire at the bottom of a tunnel on the 2.4-mile (3.9-kilometer) mountain. The cable car halted inside the tunnel; lights went out and initially the doors would not open. The narrow, 11.8-foot (3.6-meter) tunnel width left little room for evacuation. The steep (45-degree) incline turned the tunnel into a chimney, thereby blocking the escape route.

(continued on next page)

Table 4. (Continued).

Section Number	Incident	Date	Fatalities and Injuries	Brief Description
3.2.6	Mont Blanc Tunnel Fire	Mar. 24, 1999	41 fatalities, injuries not tallied	A truck carrying margarine and flour entered the 7.3-mile (11.6-kilometer) Mont Blanc Tunnel from France, caught fire, and stopped in the tunnel, where it burst into flames. The fire, fueled in part by the margarine, reached temperatures of 1,832°F (1,000°C); it trapped approximately 40 vehicles in dense and poisonous smoke.
3.2.7	Channel Tunnel Fire	Nov. 18, 1996	No fatalities, about 30 injuries	A truck on a freight train traveling from France to Great Britain caught fire, which made disconnecting the burning part of the train impossible. When the train stopped, the fire damaged the power catenary and spread to adjoining cars. The smoke moved quickly because of other trains moving in the tunnel, which also impeded evacuation. Train staff and truck drivers evacuated through a door leading to the service tunnel, but overpressure from that door created a fresh air bubble when the door was opened. Staff were rescued via the adjoining service tunnel; structural damage was considerable.
3.2.8	Subway Sarin Gas Attack	Mar. 20, 1995	12 fatalities, 5,000 to 6,000 exposed to the gas	The Aum Shinrikyo religious group released canisters of diluted Sarin on five separate trains during the Tokyo subway system's morning rush hour. As many as 6,000 people may have been exposed to the chemical; 12 people died. A review of the response highlighted a lack of coordination. Each agency (police, fire, hospitals, and other governmental units) acted under its own chain of command. This finding led to formation of a Severe Chemical Hazard Response Team.
3.2.9	Chicago Freight Tunnel Flood	April 13, 1992	0 fatalities, 0 injuries	A hole in the wall of one of the Chicago freight tunnels, 40 feet (12 meters) under the Chicago River, resulted in flooding that knocked out power throughout the Loop, forced the shutdown of the subway system, caused damage to numerous businesses, and resulted in the evacuation of about 250,000 people from the area. The flood was estimated to cost as much as $2 billion in lost revenue, tax assessment losses, and damage to the city's infrastructure.
3.2.10	London Underground (the Tube) King's Cross Station Fire	Nov. 18, 1987	31 fatalities, injuries not tallied	King's Cross station, then the busiest station in the London Underground system, is the convergence point where five Tube lines operate on four levels. There is also a ticket office below street level. A fire started in one of the four escalators linking the platform levels. The fire grew rapidly when it reached the ticket office. (The fire's rapid growth was later attributed in part to old paint and the draft created by train movements). The length and steep angle of the escalator also contributed to the fire's intensity.

Table 4. (Continued).

Section Number	Incident	Date	Fatalities and Injuries	Brief Description
3.2.11	BART Transbay Tunnel Fire	Jan. 17, 1979	1 fatality, 58 injuries	After a fire broke out in a circuit breaker in the fifth and sixth cars of a seven-car train, the train was stopped by the emergency brake and could not be restarted. An unsuccessful attempt to disconnect the burning cars delayed passenger evacuation by about 30 minutes, during which the tunnel filled with smoke despite activation of the ventilation system. Rescue involved taking the passengers out through the service tunnel. The fatality (a firefighter who died from flue gas poisoning) and injuries were caused primarily by gases from the combustion of plastics. The accident was attributed to lack of communication between the train operator and central operations, poor coordination, and errors of judgment, all of which made the incident a key factor in the development of National Fire Protection Association transit industry guidelines on responses to fire incidents [Ref. 2].
3.2.12	PATH Evacuation under the World Trade Center	Sept. 11, 2001	No fatalities, No injuries	Within minutes of the first plane striking the WTC, multiple Port Authority employees contacted the PATH control center to report that an unexplained explosion or fire had occurred. Based on direction from a PATH deputy director who was at the WTC, within 6 minutes the system's trainmaster was issuing instructions to conductors and operators to avoid the station. Had it not been for this prompt response, trains would have kept coming in at 3- and 5-minute intervals, unloading passengers directly into buildings that would soon collapse. This prompt response undoubtedly saved many lives.

older systems hadn't been upgraded since they opened. In the case of the European road tunnel accidents, inadequate planning led to traffic volumes far in excess of those anticipated. The excessive traffic volumes may have weakened the effect of the life safety and ventilation systems and contributed to post-incident problems.

The vast majority of incidents displayed communication gaps. Because all the incidents involved responses from a number of jurisdictions and agencies, the absence of advance planning and of emergency drills contributed to post-incident problems. Responses to the incidents were hampered by either an absence of procedures to follow or the failure of system employees to follow the established procedures and guidelines. The absence of preplanning of communications and emergency response, along with the lack of guidelines on whom to notify and when to notify them, added to the loss of life in some of the incidents and to the damage incurred in almost all of them.

The problems were apparent in the two primary areas of concern: prevention and mitigation. It was difficult to measure prevention because, in some cases, there did not appear to be anticipation of potential danger. It is impossible to plan to prevent or mitigate something that no one considers might occur.

The case studies demonstrate the need for the following:

- Interoperable communications networks;
- An empowered safety management team;
- An understanding of risk and vulnerability to realistically address prevention and mitigation issues;
- Pre-incident procedures, real-time emergency guidelines for operational personnel, and post-incident debriefing standards;
- Planning, upgrading, and testing of emergency systems on a regular basis;
- Inter- and intra-agency cross-training, tabletop exercises, onsite training, drills, and exercises; and
- An understanding of human factors.

The case studies also demonstrate the following realities:

- Absolute safety does not exist in tunnels.
- The highest priority must be given to securing escape routes and passages.
- The probability of accidents can be minimized through tunnel design and materials.
- The damage potential of accidents and fires can be reduced by installing emergency facilities and constructing fire-resistant tunnel structures.

Table 5. Role of MEC systems in case study incidents.

Section Number	Title	Ventilation	Life Safety Systems	Power Distribution	Command and Control	Communications
3.2.1	Moscow Subway Suicide Bombing	–	–	–	–	–
3.2.2	Jungangno (Chungang-Ro) Subway Station Arson Fire	U	U	U	–	U
3.2.3	St. Gotthard Tunnel Fire	–	F	–	–	F
3.2.4	Howard Street CSX Tunnel Fire	–	–	–	–	U
3.2.5	Kitzsteinhorn Tunnel Cable Car Fire	–	U	–	U	–
3.2.6	Mont Blanc Tunnel Fire	U	–	–	U	U
3.2.7	Channel Tunnel Fire	U	–	U	–	–
3.2.8	Subway Sarin Gas Attack	F	–	–	U	U
3.2.9	Chicago Freight Tunnel Flood	–	–	–	F	F
3.2.10	London Underground (the Tube) Station Fire	–	–	–	U	U
3.2.11	BART Transbay Tunnel Fire	U	U	–	U	U
3.2.12	PATH Evacuation under the World Trade Center	–	–	–	F	F

A "U" indicates that a particular system or operation played an unfavorable role in the incident, and an "F" indicates that a system played a favorable role. A dash indicates that the accounts do not say anything specific about the particular system.

- There is a need to change or direct tunnel user behavior.
- Tunnel operators must become more aware of four key areas:
  - Operations (ventilation and smoke extraction);
  - Infrastructure (direction of traffic, communication between tubes, and length of tunnel);
  - The sizes, types, and numbers of vehicles allowed within tunnels; and
  - Tunnel users (drivers' escape route and communications equipment).

3.4.3 Role of MEC Systems in Case Study Incidents

Although it is extremely subjective, Table 5 relates the case studies to the MEC tunnel systems that are discussed in Section 4.5. A "U" indicates that a particular system or operation played an unfavorable role in the incident, and an "F" indicates that a system played a favorable role. A dash indicates that the accounts do not say anything specific about the particular system.

CHAPTER 4

Tunnel Elements and Vulnerabilities

4.1 Introduction

When considering the role of the 550 U.S. highway and transit tunnels in the overall transportation network, and considering the lessons observed from natural disasters and the transportation-related consequences of the September 11th attacks, it is clear that loss of a critical tunnel at one of numerous “choke points” could result in hundreds or thousands of casualties; billions of dollars of direct reconstruction costs; even greater socioeconomic costs; and ancillary costs to other institutions in the nation’s complex, interrelated economy. For these reasons, transportation agencies must conduct systematic reviews to understand their facilities, identify their vulnerabilities, and develop protection strategies.

This chapter describes important elements of various tunnel construction methods used for transportation tunnels. Discussions on the failure mechanisms associated with hazards and threats are included. In addition to the construction method and general tunnel vulnerability assessment, a comprehensive description of the various tunnel liners and structural systems is provided. The critical factors that could affect structural behavior in the event of safety-related hazards or security-related threats are then introduced and related to the various features of the different tunnel systems.

The results of this chapter lead to the Chapter 5 guidelines for use by tunnel and facility owners and operators to identify (1) critical locations in tunnel structures from the operation and safety standpoints and (2) countermeasures appropriate to those critical locations.

Because of the unique features of transportation tunnels, the structural response of a transportation tunnel to a hazard or threat differs somewhat from that of a surface structure. The most notable of these features are (1) a high ratio of longitudinal length to cross-sectional dimension, (2) a complete confinement by the surrounding soils and rocks, (3) reflected pressures developed from the tunnel boundaries when an internal explosion occurs, and (4) a coupled behavior of air blast inside the tunnel and wave propagation through the surrounding ground.

An understanding of the characteristics of various types of tunnels is essential in performing an accurate vulnerability assessment. For example, an immersed tube tunnel is particularly vulnerable to rapid flooding in the event of an explosion. This high risk is due to the following features of the immersed tube tunnel: (1) the tunnel is under high hydrostatic water pressure; (2) the tunnel is surrounded by porous backfill materials; and (3) there is a limited thickness of soil cover over the tunnel. The vulnerability of an immersed tube tunnel should therefore be assessed not only from a structural damage standpoint, but also from a flooding potential standpoint. Similarly, cut-and-cover tunnels are typically built in shallow depth with limited backfill above the structures; this build reduces the amount of confinement in the vertical direction when the tunnel is subjected to either internal or external explosions. In addition, cut-and-cover tunnels are usually built in soil sites and therefore tend to be less blast resistant than tunnels surrounded by rock. Conversely, bored or mined tunnels in rock with deep cover are more resistant than those in soils with shallow cover. Therefore, the type of tunnel has a major impact on the tunnel’s vulnerability to extreme events.

4.2 Types of Transportation Tunnels

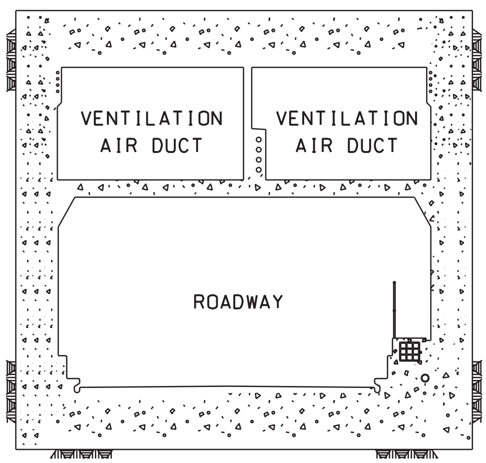
Tunnel types can be categorized to a certain extent by their usage, or mode of transportation. The functional types of tunnels included in this report are as follows:

- Road,
- Transit, and
- Rail (both passenger and freight).

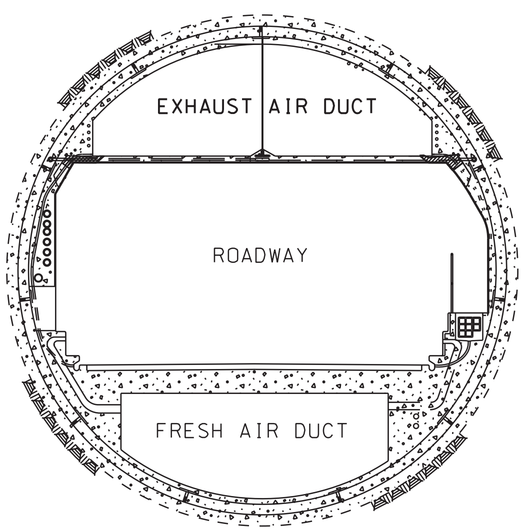
4.2.1 Typical Road Tunnels

Road tunnels that are longer than 1,000 feet (304 meters) typically have forced air ventilation systems. Prior to 1995, when the Federal Highway Administration (FHWA) approved the use of jet fans in tunnels based on results of the Memorial Tunnel Fire Ventilation Test Program (MTFVTP), the majority of tunnels were ventilated with ducted systems. A tunnel that is served by a full transverse ventilation system has a supply air duct and an exhaust air duct, and a tunnel that is served by a semi-transverse ventilation system can have either a supply duct or an exhaust duct.

In cut-and-cover tunnels, the air ducts typically run side by side to save on excavation costs, as shown in Figure 1A. In bored or mined tunnels, the ducts typically fill the available space above and below the road, as shown in Figure 1B. Tunnels served by longitudinal ventilation systems typically have ceiling-mounted jet fans in the road space in lieu of the upper ducts shown in the figures. Both of the figures depict one walkway on the right side of the road, although some multilane tunnels may have walkways on both sides. Tunnel utilities such as power and communication conduits and fire standpipes can run along the benchwall, as is shown in both sketches, or in the opposite sidewall, as shown in the bored tube tunnel.



(A) Typical cut-and-cover road tunnel.



(B) Typical bored tube road tunnel.

Figure 1. Typical road tunnels.

4.2.2 Typical Transit and Rail Tunnels

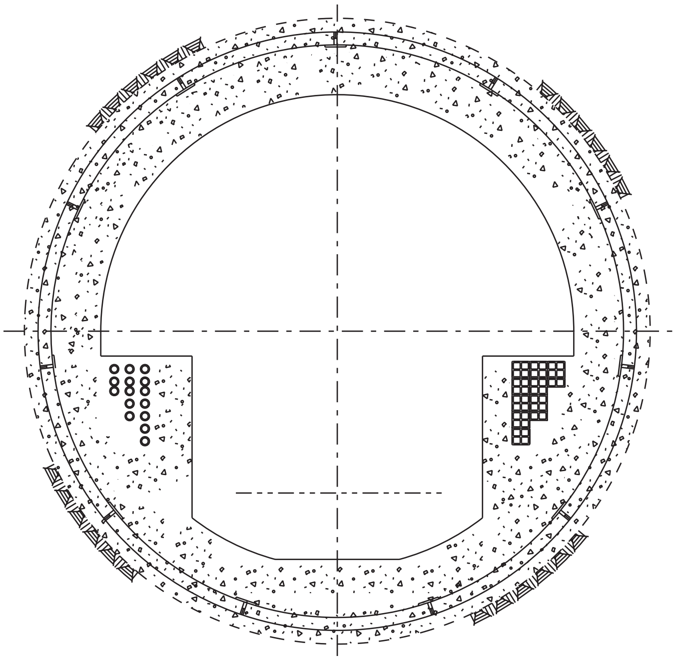
Typical transit and rail tunnels are shown in Figure 2. Shorter tunnels can be ventilated naturally by the train's piston action. Longer tunnels without forced ventilation typically have intermittent ventilation shafts that relieve the tunnel pressure through sidewalk gratings, as shown in Figure 2D. Longer tunnels with forced air ventilation can be served by midtunnel and/or end-of-station-platform fan shafts. Individual tracks in cut-and-cover transit and rail tunnels can be separated by columns, porous dividing walls, or solid dividing walls. Similar to road tunnels, utilities are routed along the tunnel benchwalls.

4.3 Tunnel Construction Methods

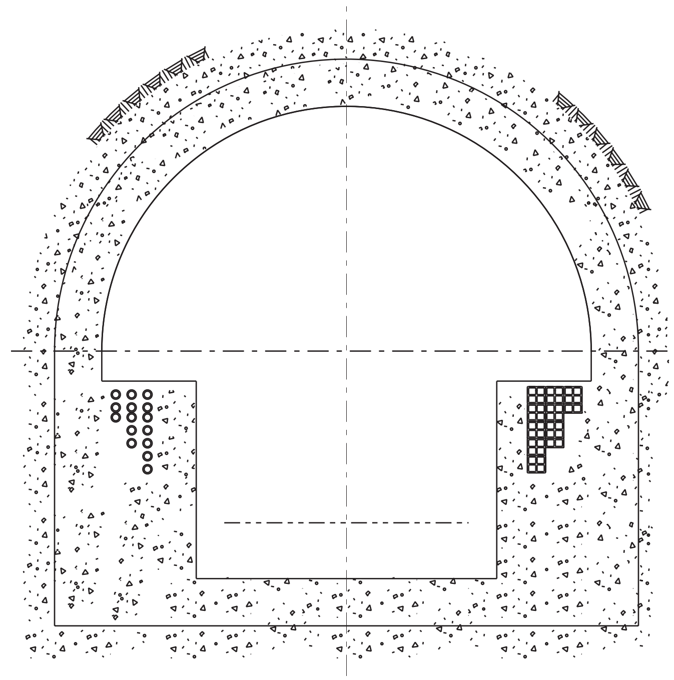
In the U.S. transportation system, tunnels have been constructed by a variety of methods, as shown in Table 6. In general, the types of tunnels are identified by the principal types of tunnel construction and include (1) immersed tube tunnels, (2) cut-and-cover tunnels, (3) bored or mined tunnels, and (4) air-rights structure tunnels. Determination of the appropriate method of construction typically depends on the depth, cross section, and soil/rock/groundwater conditions along the alignment. Other constraints include geographical and environmental factors, presence of existing structures and utilities, and constructability issues. The different materials (i.e., structural and geological), tunnel configurations, and construction procedures used for these tunnels impact their resistance to hazards and threats. It is therefore important to identify the various types of tunnels and the factors that could have a major impact on their vulnerability to hazards and threats.

4.3.1 Immersed Tube Tunnels

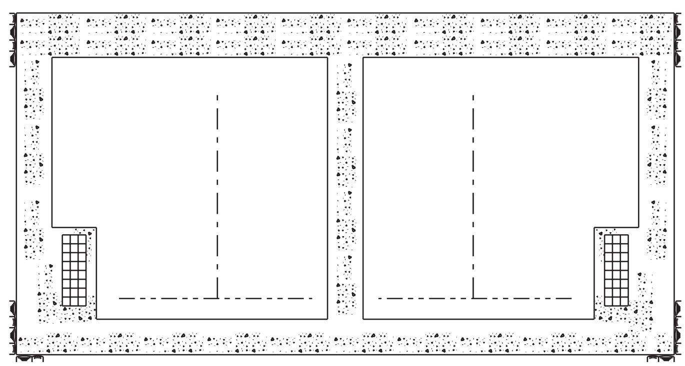
Immersed tube tunnels are employed to traverse a body of water. Tunnel sections, usually 300 to 450 feet (91 to 137 meters), are placed into a pre-excavated trench. The tunnel construction method involves (1) construction of tunnel sections in an offsite casting or fabrication facility that are finished with bulkheads and transported to the tunnel site; (2) placement of the sections in a pre-excavated trench, jointing and connecting together and ballasting/anchoring; and (3) removal of temporary bulkheads and backfilling the excavation. The top of the tunnel should be at least 5 feet (1.5



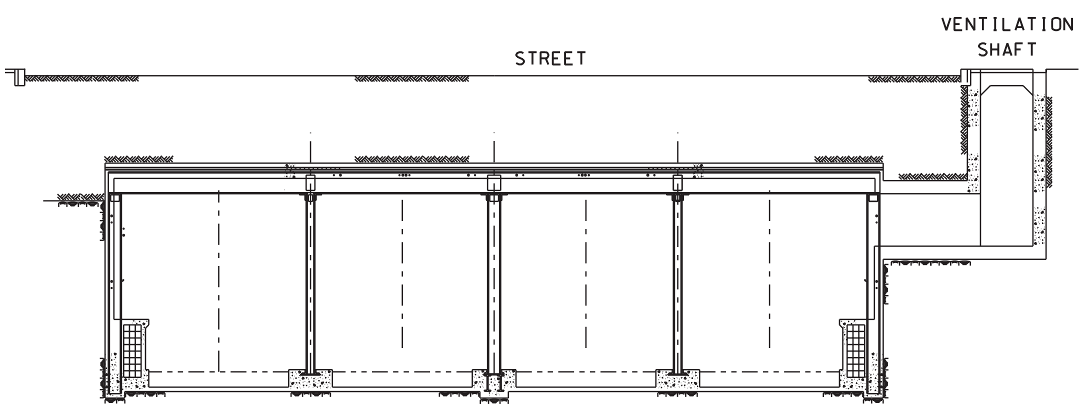
(A) Typical bored tube rail tunnel.



(B) Typical mined horseshoe rail tunnel.



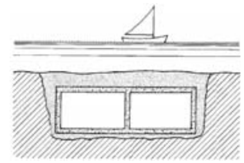
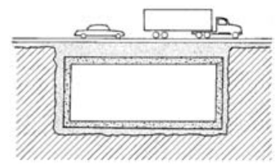
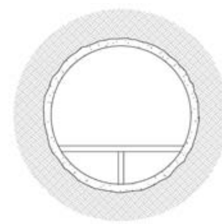
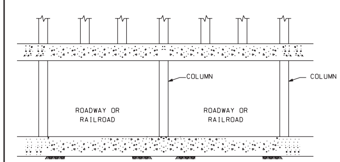
(C) Typical cut-and-cover rail tunnel.



(D) Typical cut-and-cover transit tunnel.

Figure 2. Typical transit road tunnels.

Table 6. Types of transportation tunnels.

Type	Description	Sketch
Immersed Tube Tunnel	• Employed to traverse a water body • Preconstructed sections are placed in a pre-excavated trench and connected • Typical materials include steel and concrete immersed tunnel sections • After placement, tunnel is covered with soil	
Cut-and-Cover Tunnel	• In urban areas • Excavated from the surface, then constructed in place and backfill placed to bury structure • For subway line structures, subway stations, and subsurface highway structures • Typically concrete cast-in-place or precast sections • Steel framing and concrete fill	
Bored or Mined Tunnel	• In urban or remote locations in land, on mountains, or through water bodies • Bored using a variety of techniques • Supported by initial and final support systems • Soft ground or rock tunneling • Structure may have various liner systems, including rock reinforcement, shotcrete, steel ribs and lattice girder, precast concrete segment, cast-in-place concrete, and fabricated steel lining	
Air-Rights Structure Tunnel	• In urban areas • Created when a structure is built over a roadway or trainway using the roadway's or trainway's air rights • The limits that an air-rights structure imposes on the emergency accessibility and function of the roadway or trainway that is located beneath the structure should be assessed	

meters) below the original bottom to allow for an adequate protective backfill.

Two distinct types of immersed tube tunnel construction have emerged over the years: (1) steel shell immersed tunnels; and (2) concrete immersed tunnels. Steel shell immersed tunnels are categorized according to the construction method: single-shell or double-shell construction. The first transportation tunnel constructed by immersed tube methods in the United States was completed in 1910 for the Michigan Central Railroad Tunnel under the Detroit River. The 1993 report by the International Tunnelling Association (ITA) provides a technical inventory of 91 immersed tube tunnels completed since 1910 [Ref. 3].

For the steel single-shell construction, an outer steel shell serves as a permanent watertight membrane and an exterior form for the final concrete lining. The steel shell also takes flexure forces along the exterior face of the tube before and after the placement of the concrete lining. The steel shell tube behaves as a composite steel-concrete structure after the interior concrete is completed.

Figure 3 shows a typical single-shell tube for two rapid transit tracks, separated by a service gallery and an emergency ventilation exhaust air duct. For this example, the shell plate is 3/8 of an inch (9.5 millimeters) thick and stiffened by interior transverse steel ribs spaced 6 feet (1.8 meters) on center and two longitudinal vertical interior trusses encased in the reinforced concrete walls of the gallery. The interior lining of reinforced concrete has a minimum thickness of 2 feet 3 inches (68.5 centimeters). The exterior shell is protected against corrosion by a cathodic protection system. Ballast pockets 2 feet 6 inches (78.2 centimeters) deep on top of the tube are filled with gravel to provide adequate weight to overcome buoyancy during sinking of the tube.

The basic elements of the double-steel-shell tube is a steel shell that forms a watertight membrane and, in combination with a reinforced concrete interior lining, provides the necessary structural strength for the completed tunnel. Figure 4 represents a typical double-steel-shell tube, which shows the cross section of a two-lane tunnel on an Interstate highway. In this example, the circular steel shell has a diameter of 36 feet 2 inches (11 meters) and is made of five-sixteenths inch (8 millimeters) welded steel plate. It is stiffened by external diaphragms spaced 14 feet 10 inches (4.5 meters) apart and external longitudinal stiffening ribs. The interior is lined with a minimum thickness of reinforced concrete. An exterior concrete envelope of 2-foot (61-centimeter) minimum thickness,

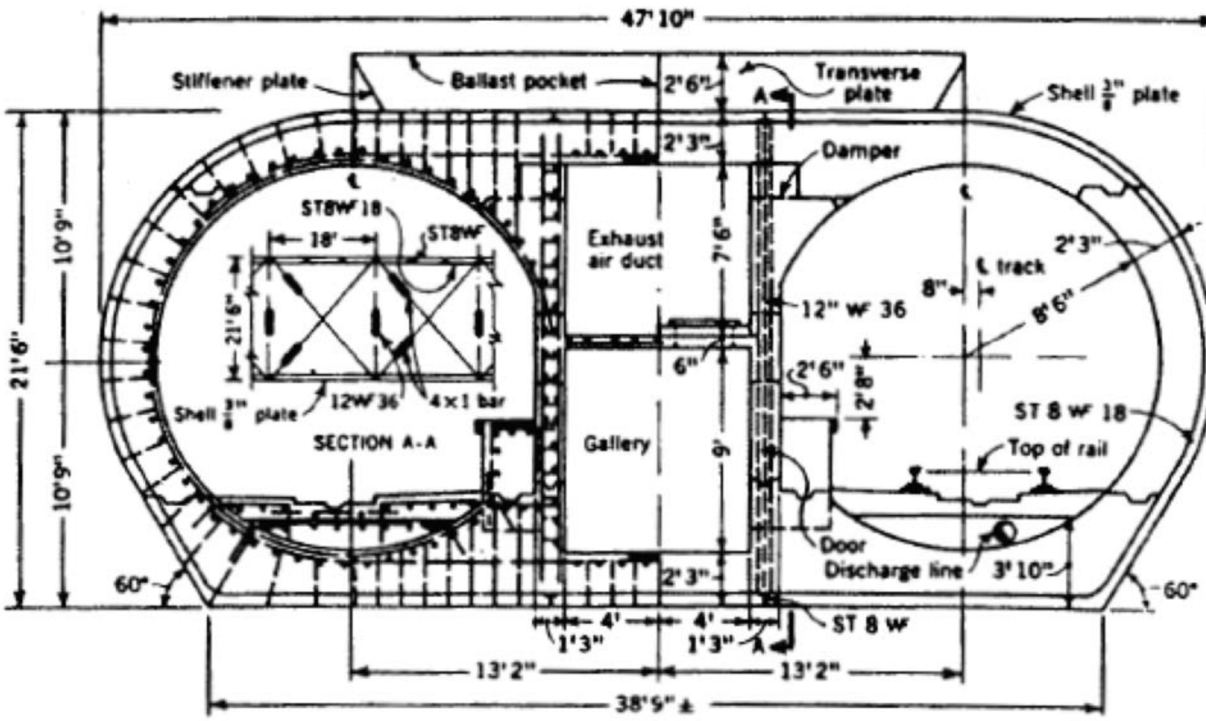


Figure 3. Steel single-shell immersed tube tunnel.

confined by one-quarter inch (6.4-millimeter) steel form plates attached to the shell, protects the shell against corrosion and acts as a ballast against buoyancy. The space below the road slab forms a fresh air supply duct. The segment above the ceiling is an exhaust duct.

Concrete immersed tube tunnels are generally rectangular reinforced concrete sections. The concrete thickness is determined largely by the weight required to prevent uplift. Crack controls to achieve impermeability of the concrete and independent waterproofing membranes are considered to accomplish water tightness. Typical waterproofing membranes used in concrete immersed tunnels are steel membranes made of one-quarter inch steel plates, multiple-ply membranes of fabric and coal-tar layers, and plastic membranes made of synthetic neoprene (or vinyl-type rubbers) with epoxy coatings. Figure 5 represents a typical concrete immersed tube for a four-lane highway tunnel with two 2-lane sections and ventilation ducts on both sides. Prestressed concrete has also been used to construct immersed tube tunnels.

4.3.2 Cut-and-Cover Tunnels

Shallow-depth tunnels in land are frequently designed as structures to be constructed using the cut-and-cover method. The cut-and-cover tunnel construction method involves braced, trench-type excavation ("cut") and placement of fill materials over the finished structure ("cover"). The excavation is typically rectangular in cross section and only for relatively shallow tunnels (typically less than 45 to 60 feet [14 to 18 meters] of overburden). Cut-and-cover tunnel structures may be divided into three types of structures in transportation systems: subway line structures, subway stations, and subsurface highway structures. Figure 6 represents a typical "line" cut-and-cover structure constructed between subway stations. In the line structures, the subway tracks are usually enclosed in a reinforced concrete double-box structure with a supporting center wall or beam with columns. The track centers are normally located as close together as possible.

The typical cut-and-cover subway station is a two- or three-story reinforced concrete structure in a rectangular excavation 50 to 65 feet (15 to 20 meters) wide, 500 to 800 feet (152 to 244 meters) long, and 50 to 65 feet (15 to 20 meters) deep. Figure 7 represents a cross section of a typical subway station. Cut-and-cover structures for older transit facilities were constructed using steel frame construction with reinforced or unreinforced concrete between the frames. This method is referred to as jack arch construction.

Cut-and-cover highway tunnels are often used in urban areas. In addition, they are often constructed at the approaches to subaqueous vehicular tunnels due to the depth required. Figure 8 represents a typical highway cut-and-cover cross section. This type of tunnel is often under the groundwater table and typically consists of massive reinforced concrete structures.

4.3.3 Bored or Mined Tunnels

When a tunnel is located at significant depth or when overlying structures exist above the tunnel alignment, bored or

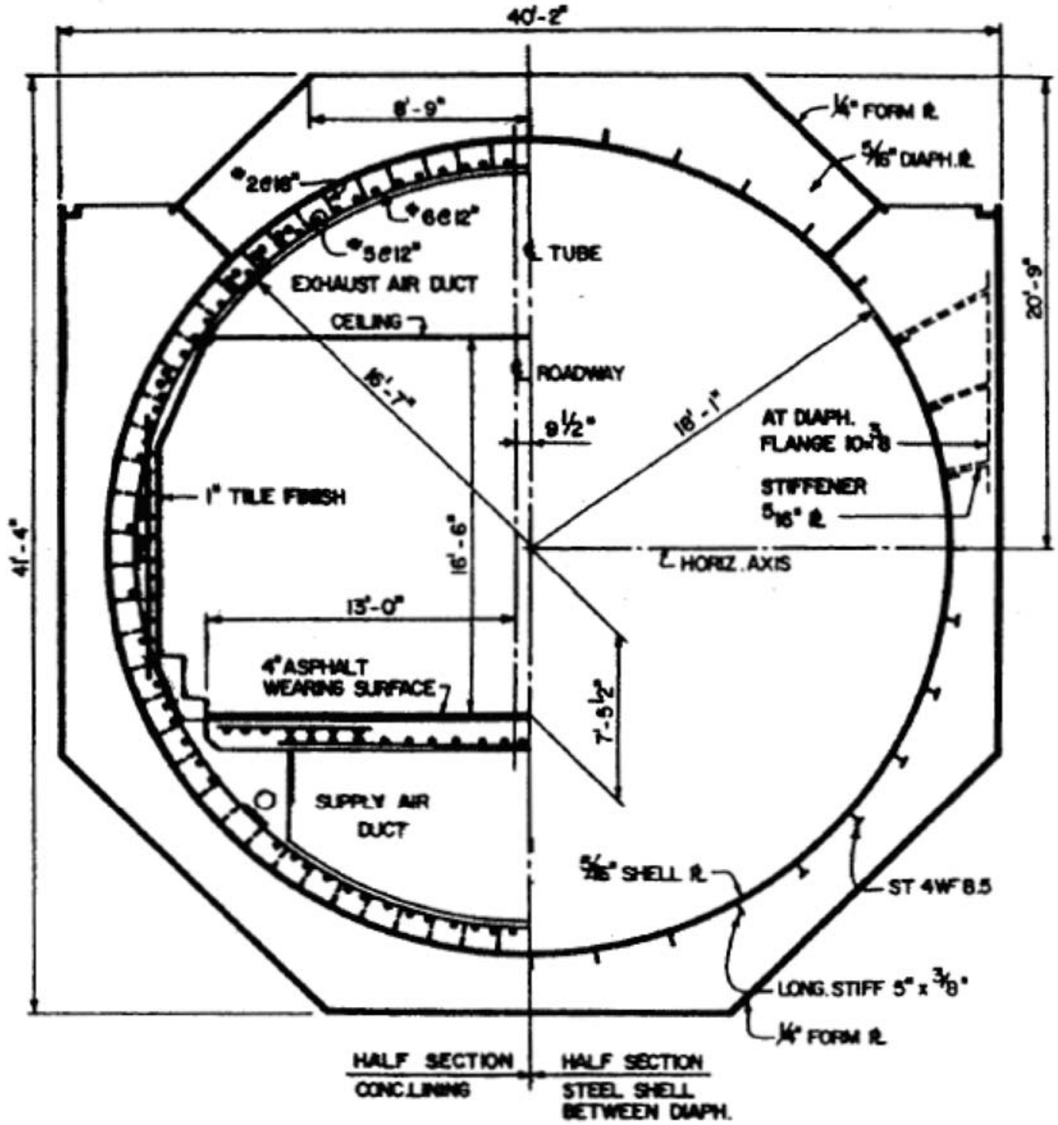


Figure 4. Steel double-shell immersed tube tunnel.

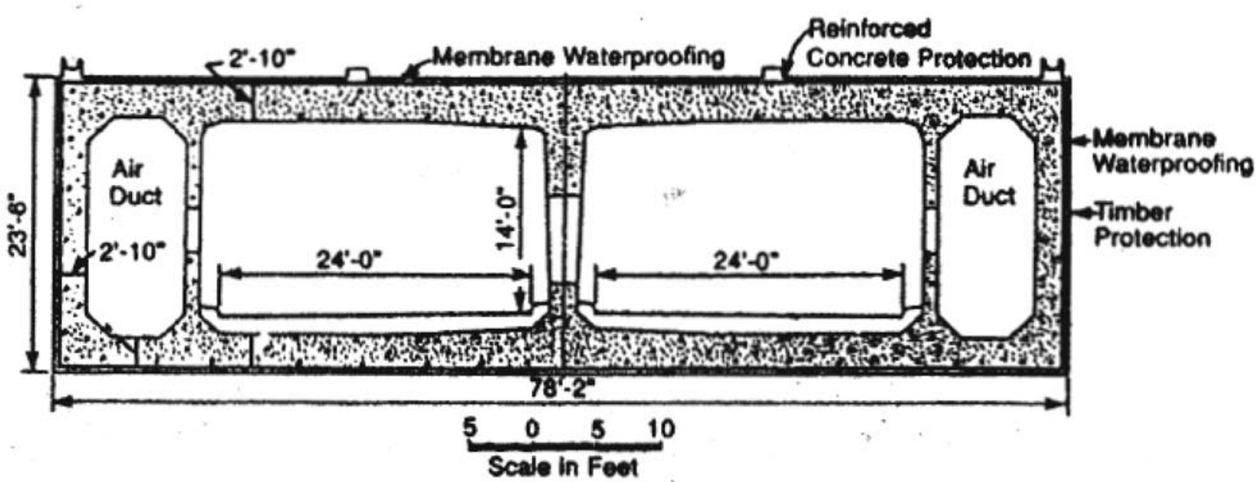


Figure 5. Concrete immersed tube tunnel.

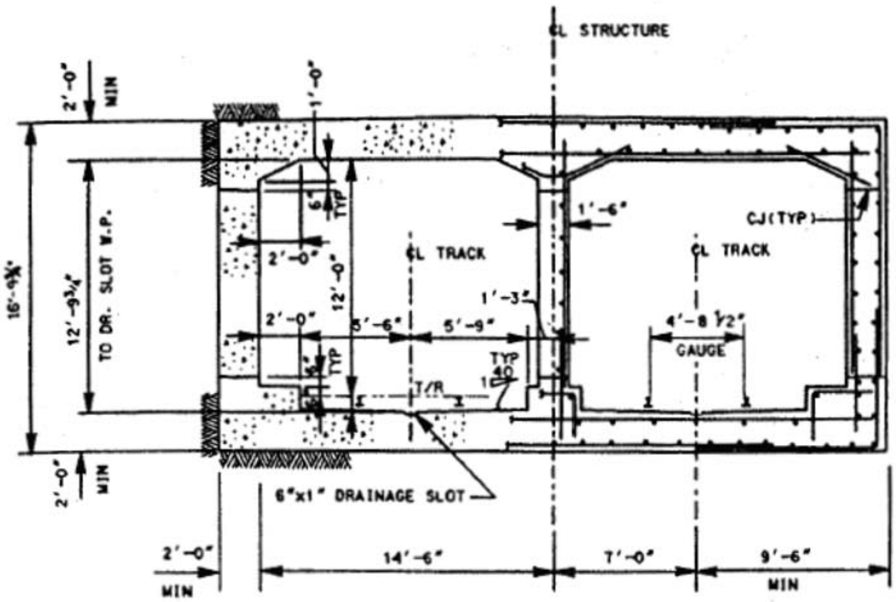
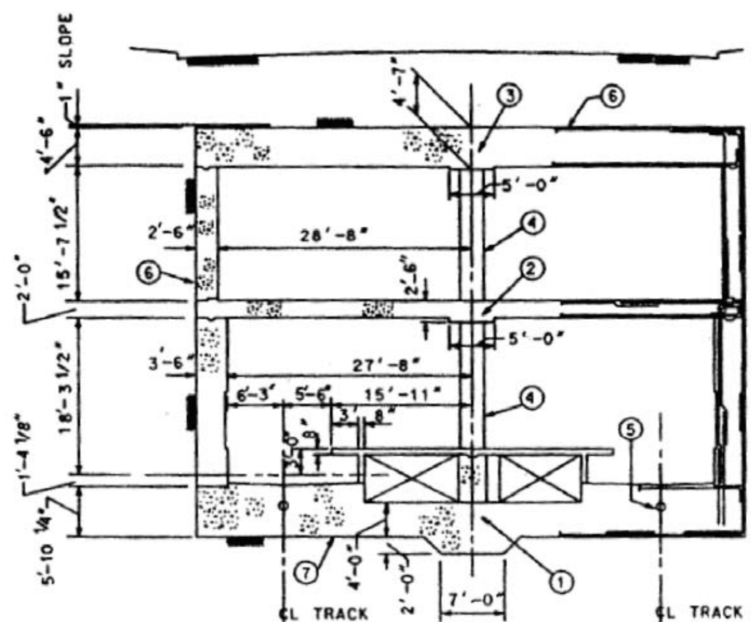


Figure 6. Cut-and-cover tunnel, subway line structure.



NOTATIONS:

1. LONGITUDINAL REINF. CONC. BASE SLAB BEAM. NOMINALLY 6'-0"x7'-0".
2. LONGITUDINAL REINF. CONC. MEZZANINE SLAB BEAM. NOMINALLY 2'-6"X5'-0".
3. LONGITUDINAL REINF. CONC. ROOF SLAB BEAM. NOMINALLY 4'-7"x5'-0".
4. ENCASED W14 COLUMN BEHIND. TYPICAL COLUMN SPACING IS 30'-0".
5. TRACK DRAIN
6. EXTERNAL WATERPROOFING IS NOT INDICATED.
7. MUDSLAB, WATERPROOFING MEMBRANE AND PROTECTION CONCRETE ARE NOT INDICATED.

Figure 7. Cut-and-cover tunnel, subway station.

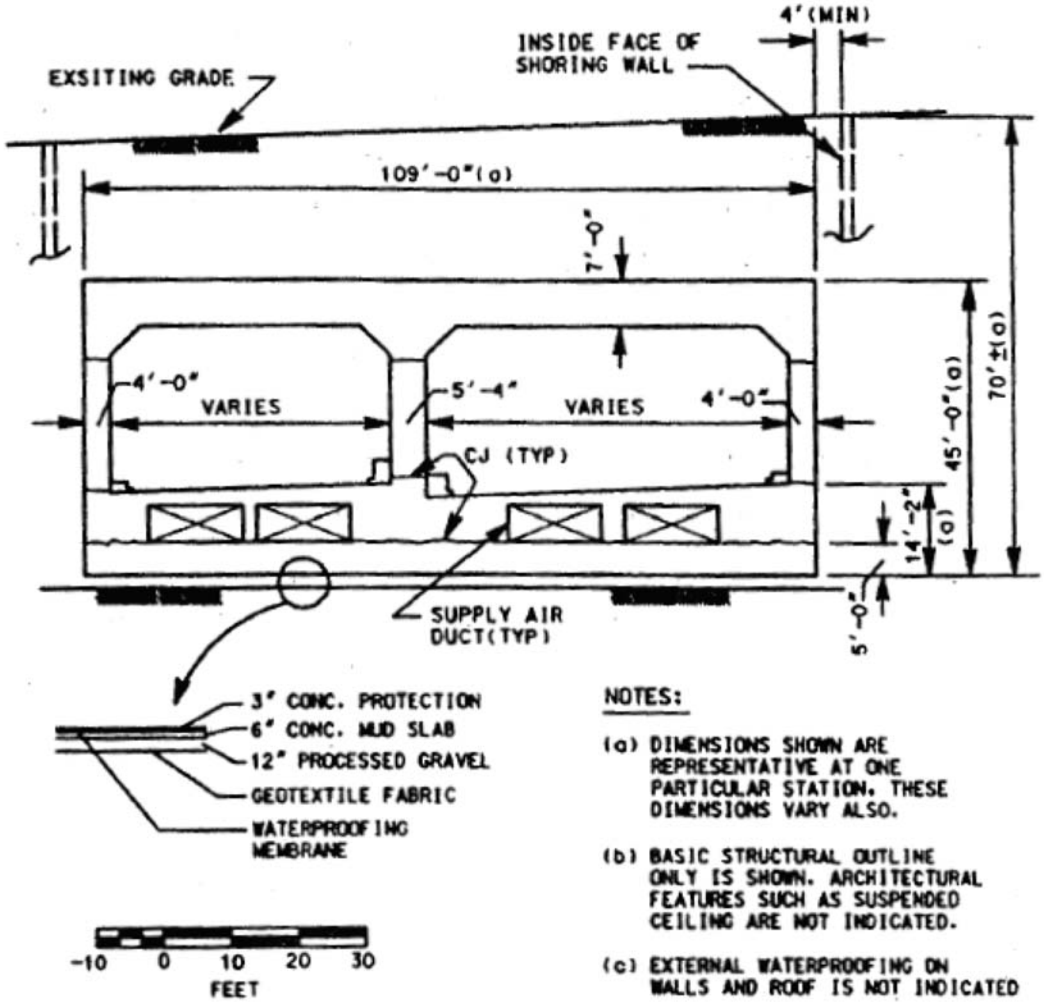


Figure 8. Cut-and-cover tunnel, subsurface highway structure.

mined underground tunnel construction is typically the preferred method. Bored tunnels are often excavated using mechanical equipment, such as TBMs, and are usually circular. Mined tunnels may be excavated using manual or mechanical methods and may be rectangular or horseshoe-shaped. Bored or mined tunnels are typically divided into two groups based on the type of surrounding ground: soft ground tunnels and rock tunnels.

For bored or mined tunnels in soft ground (i.e., soft ground tunnels), the main concerns during excavation are associated with groundwater conditions and stability characteristics of the soil along the alignment. The control of groundwater is of utmost importance in soft ground tunneling. Typical methods for controlling groundwater are dewatering, using compressed air, grouting, freezing, and using pressurized face TBMs. Recent improvements in grouting have made grouting a valuable tool in both groundwater control and soil stabilization for soft ground tunneling.

For bored or mined tunnels in rock (i.e., rock tunnels), stability problems in blocky jointed rocks are generally associated with gravity falls of rock wedges from the roof and sidewalls. A tunnel in an unweathered, massive rock with few joints does not usually suffer from serious stability problems unless stresses in the rock exceed the strength of the rock. As the below-surface depth increases or as the number of close-together excavations increases, the rock stress increases to a level at which failure is induced in the rock surrounding the tunnels. This failure may range from minor spalling or slabbing in the surface rock to major rock bursts involving failure of significant volumes of rock. Various tunneling methods used in rock and soft ground are summarized in Tables 7 and 8, respectively.

When surrounding ground is massive and rock mass is stable, the tunnel may require no support system or minimal support systems at portals and weak rock zones. When the ground is unstable, the initial support system is installed before, during, or immediately after excavation to stabilize the excavation. The final lining system is then placed to provide permanent support and to provide a durable, maintainable, long-term finish. Tables 9 and 10 show the initial support and

Table 7. Tunneling methods for rock tunnels.

Type	Description	Sketch
Tunnel Boring Machine (TBM)	• Full face advance • Circular sections • High advance rate	
Roadheader	• Partial face advance • Any cross section • Usable in rock with less than about 15,000 psi of unconfined compressive strength • Most effective if the unconfined compressive strength of rock is less than 5,000 psi	
Drill and Blast	• Conventional method • Full or partial face advance • Any cross section • Cycle involves (1) drilling; (2) charging with explosives; (3) blasting and ventilation; (4) loading and hauling (mucking); (5) scaling and cleaning; and (6) installation of a support system	

lining systems and the typical application of the initial support and lining systems, respectively.

4.3.4 Air-Rights Structure Tunnels

Air-rights structure tunnels are defined by the National Fire Protection Association (NFPA) [Ref. 5] as structures that are built over a road using the road's air rights, thereby imposing on the accessibility and operation of the road or train during emergency operations. Air-rights structure transportation tunnels have been constructed to enclose both road and rail operations.

Figure 9 shows a typical air-rights structure tunnel. The structure is supported by intermittent columns. The structure above the tunnel can be a building of any type, a transit or rail station, a parking garage or a parking lot.

These structures create transportation tunnels and may be as dangerous as the air-rights structures constructed above the roads or trains because of the relative ease of access. The damage potential of an incident in an air-rights tunnel can also be greater than those for other tunnel types because occupancy loads include the people located in the structure.

4.4 Structural Elements and Vulnerabilities

4.4.1 Ground Characteristics

Terzaghi published the Tunnelman's Ground Classification System, which describes representative soil types and their predicted behavior during various tunneling construction methods [Ref. 6]. As shown in Table 11, Heuer modified this classification system to present the information in engineering terms that reflect current technology and usage [Ref. 7].

4.4.2 Modes of Tunnel Failure

Tunnel failure can range from local spalling (i.e., local failure), local breach, partial or complete collapse, or inundation with water (i.e., global failure) to progressive failure. Figure 10 demonstrates how a threat can lead to progressive failure.

Tunnel failure modes can start from an overstress in the lining caused by explosion or fire. This overstress may lead to failure of the lining if the strength of the lining material is less than the applied stress. The failure of the lining may be restricted to be a local failure such as spalling or local breach.

When the tunnel lining is damaged locally or globally, failure of surrounding ground (i.e., collapse) and/or inundation with water (i.e., flooding) may follow. These failures are considered global failures.

It is considered a progressive failure when instability of adjacent underground structures and/or damage to surface structures is involved. Flooding of the transportation system may also be considered a progressive failure.

Lining Failure from Explosion

When an explosion occurs in a transportation tunnel, fragmentation of the liner is expected near the detonation point. Then, the peak blast pressures and gas pressures from the explosion may overstress the lining and the initial support systems. The fragments and overstress may induce failure of the liner and support systems. The extent of failure depends on charge weights, charge shapes, detonation points, types and materials of tunnel liner and support systems, thickness

Table 8. Tunneling methods for soft ground tunnels (as modified by Zosen [Ref. 4]).

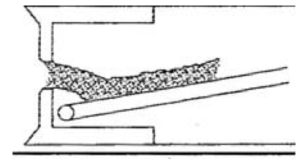
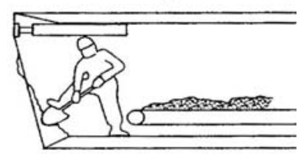
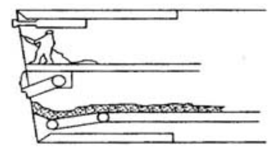
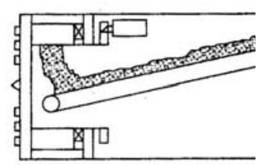
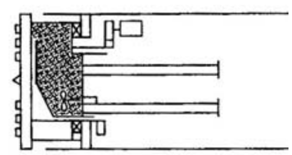
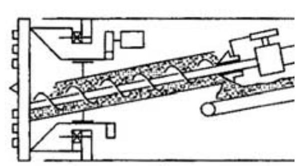
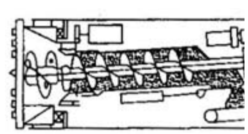
Type	Description	Sketch
Blind Shield	• A closed face (or blind) shield is used in very soft clays and silts • Muck discharge is controlled by adjusting the aperture opening and the advance rate • Used in harbor and river crossing in very soft soils; often results in a wave or mound of soil over the machine • Not used nowadays	
Open Face, Hand-Dug Shield	• Good for short, small tunnels in hard, noncollapsing soils above groundwater tables • Usually equipped with face jacks to hold breasting at the face • If soil conditions require it, this machine may have a movable hood and/or deck • A direct descendent of the Brunel Shield • Seldom used nowadays	
Semi-Mechanized	• Similar to open face, but with a back hoe and boom cutter; often equipped with "pie plate" breasting and one or more tables • May have trouble in soft, loose, or running ground • Compressed air may be used for face stability in poor ground • Seldom used nowadays	
Mechanized	• A fully mechanized machine • Excavates with a full face cutter wheel and pick or disc cutters • Manufactured with a wide variety of cutting tools • Face openings (doors, guillotine, etc.) may be adjusted to control the muck taken in versus the advance of the machine • Compressed air may be used for face stability in poor ground	
Slurry Face Machine	• Uses pressurized slurry to balance the groundwater and soil pressure at the face • Has a bulkhead to maintain the slurry pressure on the face • Good for water-bearing silts and sands with fine gravels; may accommodate boulders • Best for sandy soils; tends to gum up in clay soils; with coarse soils, face may collapse into the slurry • Can be equipped with disk cutters to bore through boulders or rock in mixed face conditions	
Earth Pressure Balance (EPB) Machine	• A closed chamber (bulkhead) face used to balance the groundwater and/or collapsing soil pressure at the face • Uses a screw discharger with a cone valve or other means to form a soil plug to control muck removal from the face and thereby maintain face pressure to "balance" the earth pressure • Best for clayey soils with acceptable conditions • Acceptable for silt and clayey and silty sand • Often uses foams and/or other additives to condition the soil • Can be equipped with disk cutters to bore through boulders or rock in mixed face conditions	
EPB High-Density Slurry Machine	• A hybrid machine that injects denser slurry (sometimes called slime) into the cutting chamber • Developed for use where soil is complex, lacks fines or water for an EPB machine, or is too coarse for a slurry machine	

Table 9. Initial support and lining systems.

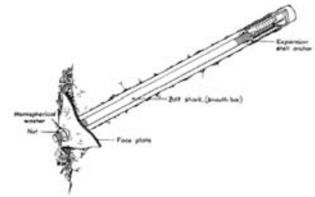
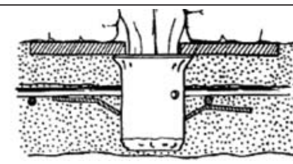
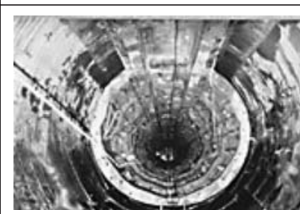
Type	Description	Sketch
Rock Reinforcement	• Untensioned rock dowels or tensioned rock bolts • To help rock mass self-support capacity and to mobilize the inherent strength of the rock mass • May provide only temporary support until a final lining is placed • To protect against spalling and fallout of rock wedges between reinforcements, a surface skin may be required such as chain link mesh or shotcrete	
Shotcrete	• Early construction support in rock with limited stand-up time to prevent loosening of the rock mass and raveling failure • Used in soft ground tunnels when a sequential excavation method (SEM) is used. • Sometimes used as a permanent lining • May be reinforced for additional long-term ductility in poor or squeezing ground	
Steel Ribs and Lagging	• Considerable appeal in poor rock conditions • Lateral spacer rods (collar braces) are usually placed between ribs • For soft ground tunnels, the ground between ribs is stabilized by lagging or by segmental plates	
Precast Concrete Segment Lining	• Usually associated with soft ground tunneling • Bolted or unbolted segments • One- or two-pass lining system • Segments are bolted with a gasket for water tightness	
Cast-in-place Concrete Lining	• Plain or reinforced • Commonly used second stage lining in two-pass lining system • Waterproofing membrane layer may be installed between initial support systems and the inner lining	
Fabricated Steel or Cast Iron Lining	• Required when leakage through a cracked concrete lining is a concern. Designed for an exterior water pressure and furnished with external stiffeners for high-external-pressure conditions • Concrete placement is required to ensure firm contact between steel and ground	

Table 10. Typical application of initial support and lining systems.

Ground	Rock Bolts	Rock Bolts with Wire Mesh	Rock Bolts with Shotcrete	Steel Ribs and Lattice Girder	Cast-in-Place Concrete	Concrete Segments
Strong Rock	•	•				
		•	•			
Medium Rock		•	•	•		
			•	•	•	
Soft Rock				•	•	•
				•	•	•
Soil				•	•	•

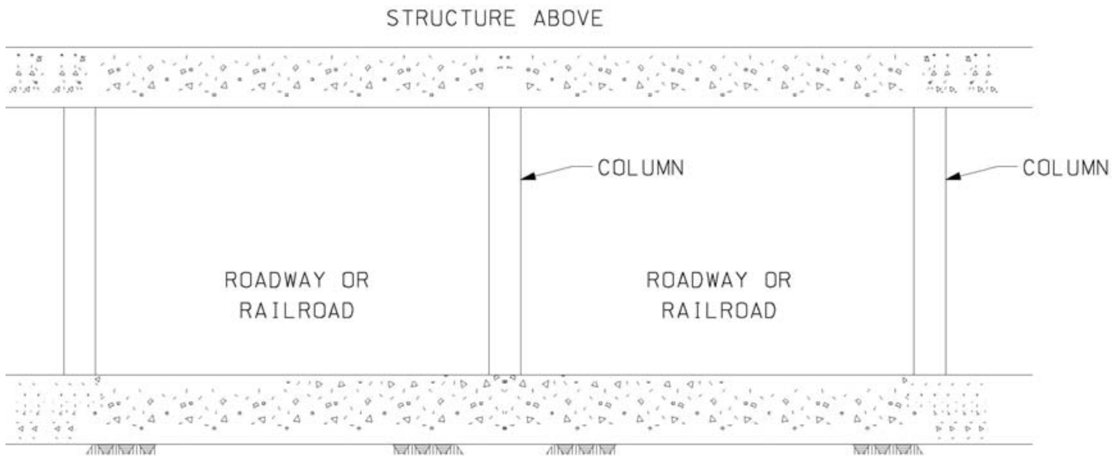


Figure 9. Typical air-rights structure tunnel.

Table 11. Tunnelman's ground classification for soils.

Classification		Behavior	Typical Soil Types
Firm		Heading may be advanced without initial support, and final lining may be constructed before ground starts to move.	Loess above water table; hard clay, marl, cement sand, and gravel when not overstressed.
Raveling	Slow Raveling	Chunks or flakes of material begin to drop out of the arch or walls some time after the ground has been exposed, due to loosening or overstress and "brittle" fracture (ground separates or breaks along distinct surfaces, as opposed to squeezing ground). In fast-raveling ground, the process starts within a few minutes; otherwise, the ground is slow raveling.	Residual soils or sand with small amounts of binder may be fast raveling below the water table and slow raveling above. Stiff fissured clays may be slow or fast depending on degree of overstress.
	Fast Raveling		
Squeezing		Ground squeezes or extrudes plastically into tunnel, without visible fracture or loss of continuity, and without perceptible increase in water content. Ductile, plastic yield, and flow due to overstress.	Ground with low frictional strength. Rate of squeeze depends on degree of overstress. Occurs at shallow to medium depth in clay of very soft to medium consistency. Stiff to hard clay under high cover may move in combination of raveling at execution surface and squeezing at depth behind surface.
Running	Cohesive Running	Granular materials without cohesion are unstable at a slope greater than their angle of repose (±30–35). When exposed at steeper slopes, they run like granulated sugar or dune sand until the slope flattens to the angle of repose.	Clean, dry, granular materials. Apparent cohesion in moist sand, or weak cementation in any granular soil, may allow the material to stand for brief periods of raveling before it breaks down and runs. Such behavior is cohesive running.
	Running		
Flowing		A mixture of solid and water flows into the tunnel like a viscous fluid. The material may enter the tunnel from the invert as well as from the face, crown, and walls, and may flow for great distances, completely filling the tunnel in some cases.	Below the water table in silt, sand, or gravel without enough clay content to give significant cohesion and plasticity. May also occur in highly sensitive clay when such material is disturbed.

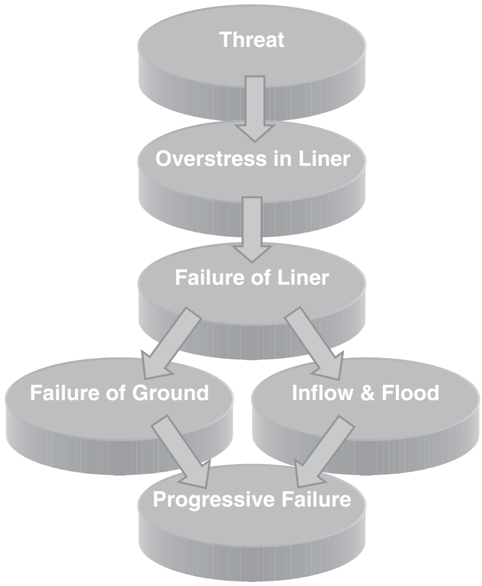


Figure 10. Path to progressive failure.

of liner, size and shape of tunnel, and type and amount of surrounding ground confinement.

When tunnel linings are subjected to extreme blast loadings, the stress–strain relationship of reinforced concrete is quite different from that under static load. This difference is due to the increased dynamic compressive and tensile strengths and the increased displacement capacity at ultimate stress. For reinforced concrete, dynamic strength magnification factors as high as 4 in compression and as high as 6 in tension for strain rates in the range of 10^2 to 10^3 per second have been reported by Grote et al. [Ref. 8]. For steel members, the U.S. Army recommends that dynamic yield strength 10 percent greater than the static yield strength be used [Ref. 9]. When the blasting induced peak overpressure is greater than the dynamic strength of the lining materials, the lining is considered overstressed. Therefore, estimation of the blasting induced peak overpressure provides a critical input in tunnel lining vulnerability assessment.

Breach failure potential may be determined by comparing breach threshold thickness and effective thickness of the tunnel lining. The liner may be considered breachable when the effective thickness of the liner is less than the breach threshold thickness. The effective thickness of the lining includes the final lining thickness and the thickness of the portion of the initial support system that can be considered a permanent application, such as shotcrete. Breach threshold thickness of normal reinforced concrete with a strength of 4,000 psi (2,812,400 kilograms per square meter) for a spherical detonation is shown in Figure 11. Breach threshold thickness is expressed as a function of explosive charge weight and setback distance (i.e., the distance from the face of the lining to the center of the charge) [Ref. 10]. Note that Figure 11 is not applicable for contact charges. This information allows a rough assessment of the tunnel lining vulnerability to an explosion inside the tunnel.

Joint Failure

Joints between immersed tube segments or between the end tube and the connecting structures (e.g., ventilation buildings) may be potential weak points in the structural system and may be more susceptible to flooding in case of

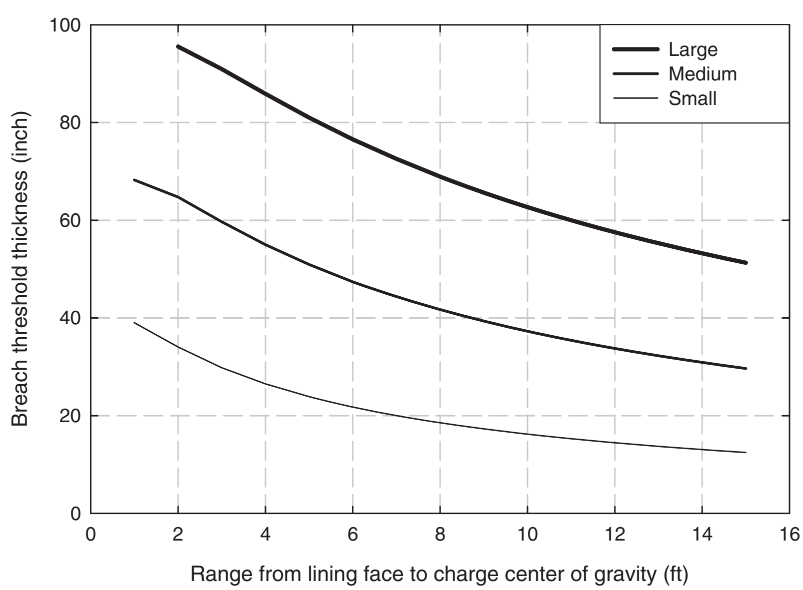


Figure 11. Breach threshold thickness for reinforced concrete [Ref. 10].

breach. There are various types of joints used in immersed tube tunnels:

- **Tremie joints:** These joints have been used in a number of steel shell tubes in the past, but have rarely been used recently. The tremie joints in one particular underwater tunnel are steel formed in soil trenches and rock encased in rock trenches. For these tremie concrete joints, the steel reinforcement and the steel plate were welded and continued through the joints after internal dewatering. Thus, in this case, they are as strong as the main body of the tunnel. The tremie concrete is anticipated to provide additional resistance to loading resulting from blast waves.
- **Flexible joints:** The initial seal of the flexible joint is provided by the compression of rubber or neoprene gaskets attached to the face of one tube and bearing against a smooth surface on the adjoining tube. Many tunnels in the United States have used temporary gaskets that may form a seal, but the load is carried on solid stop bars. The two most recently built tunnels in the United States have used Gina-type joints that have soft noses and bodies capable of carrying the compressive load. Particularly in seismic areas, the flexible joints are designed to carry expected shear and tension loads and may sometimes be referred to as seismic joints. In such cases, a joint cannot open or have offset displacements under seismic loading conditions, which could lead to life-threatening ingress of water. This type of joint presents potential weakness for ingress of water and flooding under blast wave conditions resulting from detonation of an explosive.
- **Rigid joints:** Rigid joints may be designed to have the same section properties as the rest of the tunnel, effectively making the tunnel continuous without joints. The resistance of the joints is therefore the same as the tunnel lining.

Cross Passageway Failure

The general lining response of cross passageway tunnels subject to blast loading is approximately the same as described above. Special attention should be given to the following considerations: (1) high stress concentration may occur at the junctions with main tunnels and (2) given the same amount of explosive charge, the resulting blast peak pressure in a cross passageway tunnel may be greater than that in the main tunnel due to its smaller cross-sectional geometry. Therefore, cross passages are more vulnerable to damage. In general, however, from an operational standpoint, cross passageway tunnels are not considered to be more critical than the main running tunnels because (1) there is generally more than one cross passageway tunnel (i.e., greater degree of redundancy) and (2) local failure or collapse of one or more of the cross passageway tunnels may not affect the stability of the main tunnels or prevent their continuous use, except when flooding results.

Portal Failure

From a stability standpoint, the tunnel portal area is generally one of the critical locations due to the inherent slope stability problem. Landslide, rock fall, or even collapse at and near tunnel portals may be triggered by certain extreme events, such as earthquakes and blast waves, thereby blocking the passageway and potentially affecting structures or facilities at the top of the slope. Tunnel portals are therefore considered to be particularly vulnerable during such extreme events. However, at the portal, the blast is less confined and the energy will dissipate. To stabilize the portal area, soil anchors or rock reinforcement systems are often used. Other remedial measures, such as flattening the earth slopes or using various ground improvement treatments, may also be effective. Nevertheless, the damage potential of a portal failure is generally considered to be less than that of a tunnel lining failure because the repair for a portal failure can be done in the open space. In addition, flooding is normally not an issue when a portal is damaged or collapses, so the repair time and associated costs are relatively low compared with the other parts of the tunnel.

Ground (Soil and Rock) Failure

Blasting may also cause the geological media surrounding the tunnel to yield or fail, particularly when the tunnel liner is breached or in unlined tunnels (such as those constructed in sound rock). The post-yield behavior of the surrounding geological media depends on the types of the materials encountered and their characteristics under high-energy transient loads. Following is a brief description of post-yield behavior of various types of soils and rocks:

- **Sand and gravel:** These materials may quickly collapse into the tunnel. When sand and gravel are saturated with water, semi-flowing to flowing conditions may occur. Flooding of the tunnel could also happen if the surrounding material is very porous (such as gravel or rock fill) under a high groundwater level. This is particularly true for immersed tube tunnels.
- **Soft cohesive soils:** Because of its low strength, soft cohesive soils, such as clay and silt, could demonstrate slow flowing behavior (i.e., creeping), eventually collapsing into the tunnel.
- **Stiff and highly overconsolidated cohesive clay:** Local failure of this type of material into the tunnel is likely.

The material falling into the tunnel should be confined to the area where the liner is breached.

- **Shear zone, broken, or decomposed rocks:** Depending on whether the shear zone is saturated with groundwater, the materials may advance into the tunnel under flowing, swelling, and squeezing conditions.
- **Plastic, ductile rock:** This type of rock, such as shale, behaves similarly to the overconsolidated clay described above. It may yield without losing its coherence and thus provides self-support capability for a short duration.
- **Fractured rock held in place by support of dowels or shotcrete:** The rock mass may yield with small to moderate displacements along fractures. Fresh fractures could be generated, thereby resulting in some loosened rock pieces falling into the tunnel.
- **Fractured rock without reinforcement:** Upon blasting loads, this material tends to become severely loosened, thereby resulting in a raveling situation.
- **Stronger, brittle rock:** Fractures and local spalling could occur. Chunks of rock loosened by the explosion could fall into the tunnel.

Water Inflow and Flooding

Transportation tunnels are intensively concentrated and interconnected in urban areas. Therefore, failure of an underwater tunnel ranging from collapse or complete inundation with water due to local breaching of the liner may lead to flooding in the underground transportation system. Flooding may also introduce large quantities of sand, silt, gravel or shear zone debris. Significant lengths of tunnel can become filled with debris or mud in short periods of time, causing tunnel structures to become buried. In addition, loosening of the soil under foundations can undermine structures above or adjacent to the tunnel.

Progressive Failure

Failure of the tunnel liner and surrounding ground may cause instability of adjacent underground utilities and damage to surface structures by piping and differential settlements. Flooding of the entire transportation system may also be considered a progressive failure.

4.4.3 Effects of Other Extreme Events

Tunnel Lining Behavior During a Fire

There are three primary adverse effects on concrete or shotcrete tunnel linings that are subjected to fire:

- The lining may lose its effective section area by spalling,
- The material strength and load-carrying capacity of the lining may be degraded when exposed to high temperatures resulting from the fire, and
- Tunnels tend to be thermally restrained in both longitudinal and transverse directions, resulting in increased structural demand under fire conditions.

Fires in tunnels may lead to a high risk of explosive spalling of the concrete liner, particularly for concrete with high moisture content, such as shotcrete, or for high-performance or high-strength concrete with low permeability. Explosive spalling occurs in the temperature range where chemically bound water is released from the concrete. Explosive spalling of high-performance or high-strength concrete is directly related to internal pressures generated during the attempted release of chemically bound water.

Lawson et al. characterized the residual mechanical properties of high-performance or high-strength concrete after the concrete is exposed to elevated temperatures [Ref. 11]. Using results from a combination of a heat transfer analysis and a nonlinear structural analysis conducted for a range of service loads, concrete mixes, and fire types, Caner et al. proposed a guideline for assessing fire endurance [Ref. 12]. The effects of temperature-induced material degradation and ground tunnel liner interaction were considered in these analyses. Caner et al. also recommended techniques for repair of damaged concrete tunnel liners, as summarized below:

- **Concrete sections:** Concrete sections exposed to temperatures in excess of 300°C (570°F) should be investigated. They should be removed or replaced if they are found to be deficient. The depth of fire-damaged concrete may be determined by using heat transfer analyses and should be verified by condition assessment. Voids and spalls should be patched with patching materials of similar characteristics as the concrete mix design used for the original tunnel to maintain its structural integrity.
- **Reinforcement:** If the concrete is removed around the reinforcement, reinforcement shall also be removed. High-strength alloy bars may lose 40 percent of their initial strength at 500°C (930°F). The new reinforcement should be properly spliced to the existing reinforcement.
- **Micro-polypropylene fibers:** Use of micro-polypropylene fibers in concrete will reduce explosive spalling because the fibers will melt over 130°C (270°F), making the concrete more porous, thus accommodating water vapor during a fire. An evaluation of the need for major repair should be determined on a case-by-case basis. Furthermore, with the more permeable concrete, the chance of explosive spalling may be minimal in the event of another fire.
- **Insulation materials:** If the tunnel lining is insulated by the placement of coatings, and the insulation materials are

damaged, they should be replaced by the same type of material because of the fire performance history of the material. For practicality, spray-on insulation materials may be used to patch the damaged area.

The MTFVTP consisted of 98 full-scale fire tests conducted in the abandoned Memorial Tunnel. Various tunnel ventilation systems and configurations were operated to evaluate their respective smoke and temperature management capabilities. The fire sizes ranged from 34.1 to 341 MBTU per hour (10 to 100 MW). For fires below 170.5 MBTU per hour (50 MW), only cosmetic damage to the tunnel structure was observed (mainly loss of ceramic tiles from the walls and ceiling). For the 170.5 MBTU per hour (50 MW) tests, spalling of ceiling concrete was observed. The areas that resulted in exposed reinforcing steel were repaired with reinforced shotcrete. The repaired areas were not further damaged during the 341 MBTU per hour (100 MW) tests. Test results are available from Bechtel/Parsons Brinckerhoff [Ref. 13] and on CD at www.tunnelfire.com/cd.htm.

Full-scale fire tests were also conducted in Norway's Runehamar Tunnel in association with the UPTUN (UPgrading methods for fire safety in existing TUNnels) Research Program [Ref. 14]. Insulated boards with high-temperature resistance were installed to protect the tunnel surfaces. A total longitudinal distance of 75 meters was protected. The boards were installed along the first 25 meters downstream of the fire site. Ceramic curtains were installed beyond the boards; 9 meters upstream and 41 meters downstream were covered. The highest gas temperature measured was 1,365°C. Significant spalling of the tunnel material occurred both upstream and downstream of the passive fire protection system.

Earthquake Effects on Tunnels

Underground structures are generally less vulnerable to earthquakes than surface structures, such as buildings and bridges, because the surrounding ground confines underground structures. As long as the surrounding ground is stable and experiences only small ground deformations, the tunnel tends to move along with the surrounding ground and maintains its structural integrity.

In a broad sense, earthquake effects on underground tunnel structures may be grouped into two categories:

- **Ground shaking** refers to the vibration of the ground produced by seismic waves propagating through the earth's crust. The area experiencing this shaking may cover hundreds of square miles near the fault rupture. As the ground is deformed by the traveling waves, any tunnel structure in the ground will also be deformed.
- **Ground failure** broadly includes various types of ground instabilities such as faulting, landslides, liquefaction, and tectonic uplift and subsidence. Each of these instabilities can be potentially catastrophic to tunnel structures, although the damage is usually localized. It is often possible to design a tunnel structure to account for ground instability problems, although the cost may be high. For example, with proper and often expensive ground improvement techniques and/or earth-retaining measures, it may be possible to remedy the ground conditions against liquefaction and landslides.

Vulnerability Screening for Geotechnical Hazards and Threats. The discussions above show that it is important to perform a tunnel vulnerability screening study for ground failure potential (i.e., geotechnical or geological hazards and threats) prior to more detailed evaluation. The objective of the vulnerability screening process is to identify which sections of the tunnel structures may have risk of poor performance during earthquakes. For sections identified to have low earthquake risk, no further evaluations are required. Otherwise, further assessments may be needed. Factors to be considered during this screening process include, but are not limited to, the following:

- **Liquefaction potential:** Liquefaction potential exists in loose granular soils below the groundwater table only. To assess site-specific liquefaction potential in areas where liquefaction is possible, procedures based on the standard penetration test (SPT) blow count number from soil borings and/or based on cone penetration test (CPT) data can be used. Both methods compare the soil liquefaction resistance (through SPT or CPT data) with the earthquake induced dynamic stresses. Detailed information about liquefaction and the recommended procedures for evaluating liquefaction procedures are documented in the report from the 1996 workshop sponsored by the National Center for Earthquake Engineering Research (NCEER) [Ref. 15].
- **Slope stability:** In general, a seismically induced landslide through a tunnel can result in large, concentrated shearing displacements and intense damage to the structure. Evaluations should focus on the following areas: (1) at tunnel portals (in soil as well as in rock), (2) in shallow parts of the tunnel alignment adjacent to soil slopes, and (3) in areas where existing slopes have displayed signs of movement under static conditions. The commonly used pseudo-static method of analysis can be used for evaluating the seismic stability in areas of concern. If a pseudo-static seismic stability analysis indicates an insufficient safety margin against the landslide movements, then a more refined deformation-based method of analysis should be used to estimate the

movements. The impact of the potential slope movements on the affected structures should then be assessed.

- **Shear/fault zones:** If a shear/fault zone crosses the tunnel alignment, the potential relative movement along the weak plane and its effects on the tunnel structure need to be evaluated. In general, it may not be economically or technically feasible to build a tunnel to resist potential faulting displacements, particularly if the magnitude of the fault displacement is large (e.g., several feet). However, avoidance of faults may not always be possible, especially for tunnel systems that are spread over large areas. In highly seismic areas such as California, it may be inevitable for the tunnel to cross a fault. The design approach to this situation is to accept the displacement, localize the damage, and provide means to facilitate repairs.
- **Abrupt changes in structural stiffness or ground conditions:** Stress concentrations often occur in abrupt stiffness change conditions. Special attention should be paid to the following locations: (1) at a tunnel's junctions; (2) where a tunnel section traverses multiple distinct geological media with sharp contrast in stiffness (such as a shaft rising from solid rock formation up through soft soil overburden to the ground surface); and (3) where a regular tunnel section in soft ground is connected to rigid station end walls or a rigid, massive structure such as a ventilation building or shaft.

Tunnel Response to Ground Shaking. The response of a tunnel to seismic shaking motions may be described in terms of three principal types of deformations: (1) axial deformation, (2) curvature deformation, and (3) ovaling (for circular tunnels such as bored tunnels) or racking (for rectangular tunnels such as cut-and-cover tunnels). Axial deformations are induced by components of seismic waves that propagate along the tunnel axis (i.e., longitudinal response of the tunnel). When the component waves produce particle motions parallel to the longitudinal axis of the tunnel, they cause alternating axial compression and tension strains, as illustrated in Figure 12A. Curvature deformations result from component waves that produce particle motions in the direction perpendicular to the tunnel axis. The curvature deformation results in bending and shear demands on the tunnel structure, as shown in Figure 12B. The ovaling or racking deformation (i.e., the transverse response of the tunnel) is caused primarily by seismic waves propagating perpendicular to the tunnel longitudinal axis. Vertically propagating shear waves are generally considered the most critical type of waves for this mode of deformation, as shown in Figure 13 [Ref. 16].

Tunnel Damage Potential Due to Ground Shaking. Dowding and Rozen reported 71 cases of tunnel response to

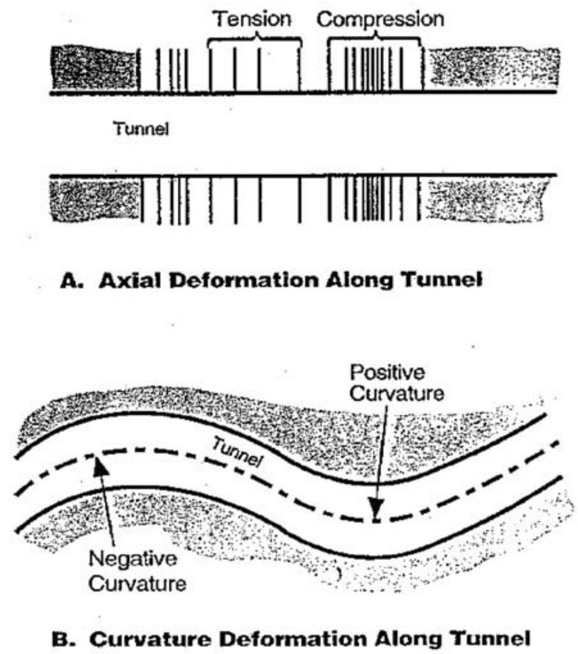


Figure 12. Longitudinal deformation of tunnels.

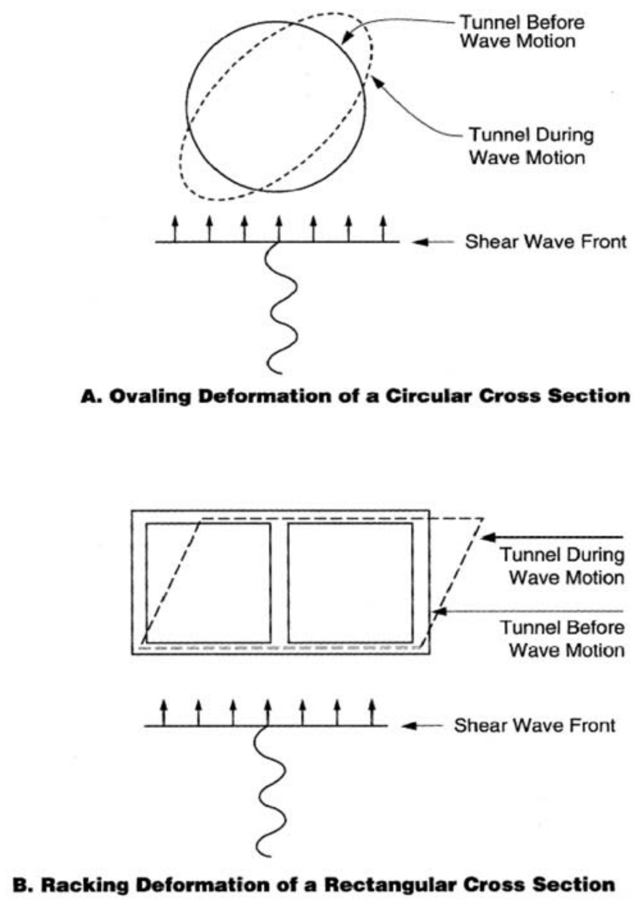


Figure 13. Transverse ovaling and racking of tunnels.

earthquake motions [Ref. 17]. The main characteristics of these case histories are as follows:

- These tunnels served as railway and water links with diameters ranging from 10 to 20 feet (3 to 6 meters).
- Most of the tunnels were constructed in rock with variable rock mass quality.
- The construction methods and lining types of these tunnels varied widely. The permanent ground supports ranged from no lining to timber, masonry brick, and concrete linings.

Based on their study, Dowding and Rozen concluded, primarily for rock tunnels, the following:

- Tunnels are much safer than aboveground structures for a given intensity of shaking.
- Tunnels deep in rock are safer than shallow tunnels.
- No damage was found in both lined and unlined tunnels at surface accelerations up to 0.19 *g*.
- Minor damage consisting of cracking of brick or concrete or falling of loose stones was observed in a few cases for surface accelerations above 0.25 *g* and below 0.4 *g*,
- No collapse was observed due to ground shaking alone up to a surface acceleration of 0.5 *g*.
- Severe but localized damage, including total collapse, may be expected when a tunnel is subject to an abrupt displacement of an intersecting fault.

Owen and Scholl documented additional case histories (making a total of 127), including cut-and-cover tunnels and culverts in soils [Ref. 18]. Owen and Scholl's conclusions form their study echoed the findings by Dowding and Rozen discussed above. In addition, Owen and Scholl suggested the following:

- Damage to cut-and-cover structures appeared to be caused mainly by the large increase in the lateral forces from the surrounding soil backfill.
- Duration of strong seismic motion appeared to be an important factor contributing to the severity of damage to underground structures. Damage initially inflicted by earth movements, such as faulting and landslides, may be greatly increased by continued reversal of stresses on already damaged sections.

Using the data presented above as well as additional data from the 1995 Kobe, Japan, earthquake (with a moment magnitude of 6.9), Figure 14 summarizes empirical observations of seismic effects on the performance of bored tunnels [Ref. 19]. The damage state is presented as a function of ground shaking levels (represented by peak ground acceleration) and tunnel lining types. The data apply only to damage due to shaking. Data for cut-and-cover and immersed tunnels are not included in the figure.

4.4.4 Critical Factors in Vulnerability Assessment of Transportation Tunnels

Because of the nature of underground structures, the vulnerability of a tunnel must be assessed by considering the interactive effects of the blast pressure, the structure, and the surrounding ground. The critical factors that could have an impact on structural vulnerability in response to hazards and threats are summarized below:

- **Type of tunnel (i.e., construction type):** In general, immersed tube tunnels and cut-and-cover tunnels are more vulnerable than bored or mined tunnels because of the typical shallow soil cover and the nature of the backfill material surrounding the tunnels. If an immersed tube tunnel is breached, the result could be rapid flooding in the tunnel and potential flooding of significant portions of the underground transit system if they are connected.
- **Geological medium (i.e., ground type):** Stronger and more competent rock (accounting for the rock joints and discontinuity effects) provides better tunnel confinement and therefore more resistance to explosions. Even a large blast inside a tunnel in good rock will likely induce only limited local damage and could be easily repaired within a reasonably short period. Tunnels constructed in soil tend to be more vulnerable than those in rock. Tunnel structure elements in very soft soil will induce larger bending and shear demands under blast loading conditions. Underwater tunnels surrounded by very porous material (such as immersed tunnels backfilled with gravel or rock fill) are particularly vulnerable to the inflow of large volumes of water mixed with surrounding materials.
- **Soil or rock overburden:** Structural damage potential increases with decreasing soil or rock cover. Deeper cover provides better tunnel protection from both interior and exterior explosions.
- **Groundwater conditions:** For a tunnel surrounded by semi-flowing water (e.g., an immersed tunnel backfilled with gravel-sized backfill) or flowing water (e.g., an immersed tunnel backfilled with coarse rockfill material), the damage potential may be severe because of flooding and associated damage to the operating systems. For a tunnel on land, better tunnel performance can be expected when it is surrounded by a dry geological medium (i.e., when there is a low groundwater level) than when it is surrounded by a wet geological medium (i.e., when there is a high groundwater level).

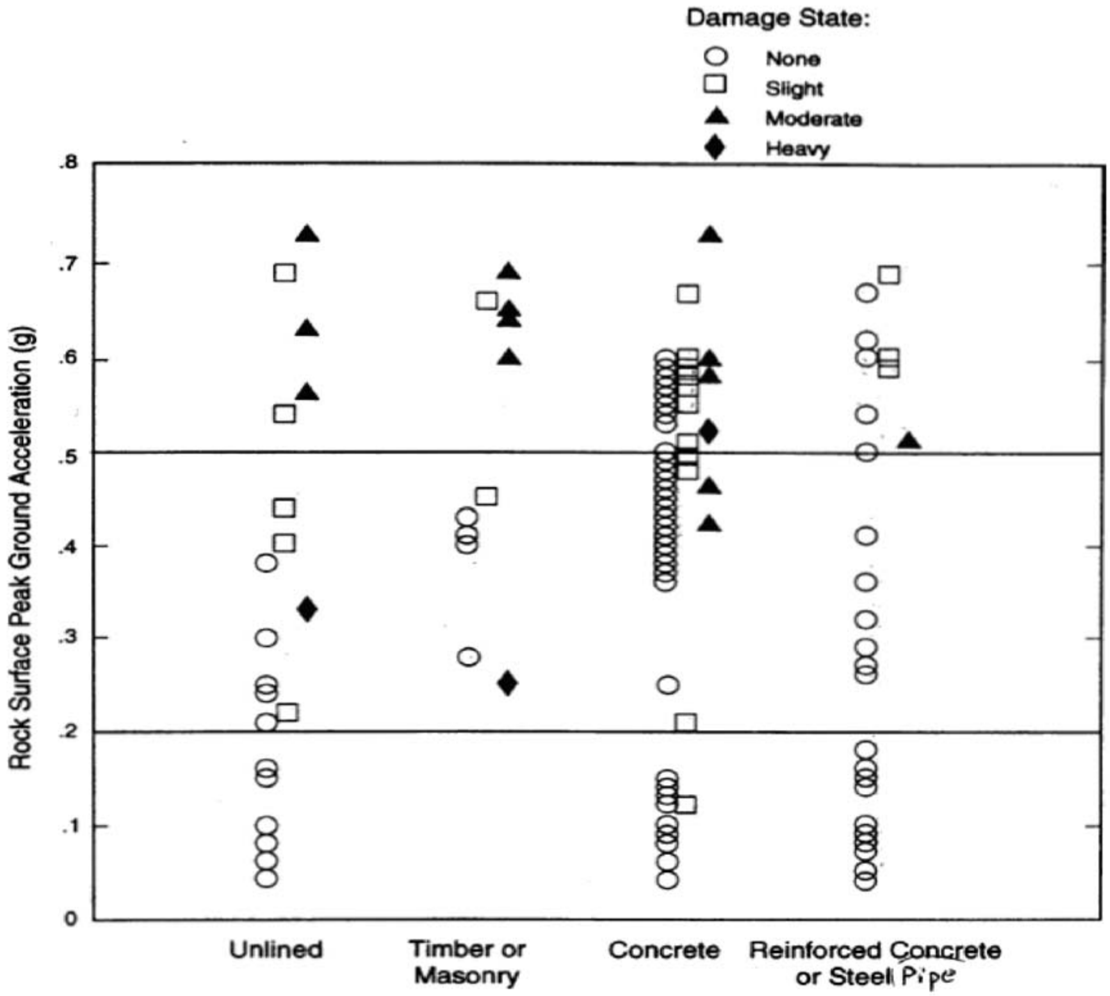


Figure 14. Empirical correlation of seismic ground shaking induced damage to bored tunnels [Ref. 19].

- **Properties of structure, liner, and initial support:** In general, a structural liner with greater thickness, greater relative structure or ground resistance, more confinement reinforcement (in concrete lining), higher ductility, and better framing design (e.g., moment-resisting properties) tends to perform better under extreme loading events, especially if high external confining pressures exist. As mentioned previously, Figure 11 presents a rough estimate of the required tunnel liner thickness (for reinforced concrete) as a function of the explosive charge weight and the charge standoff distance.

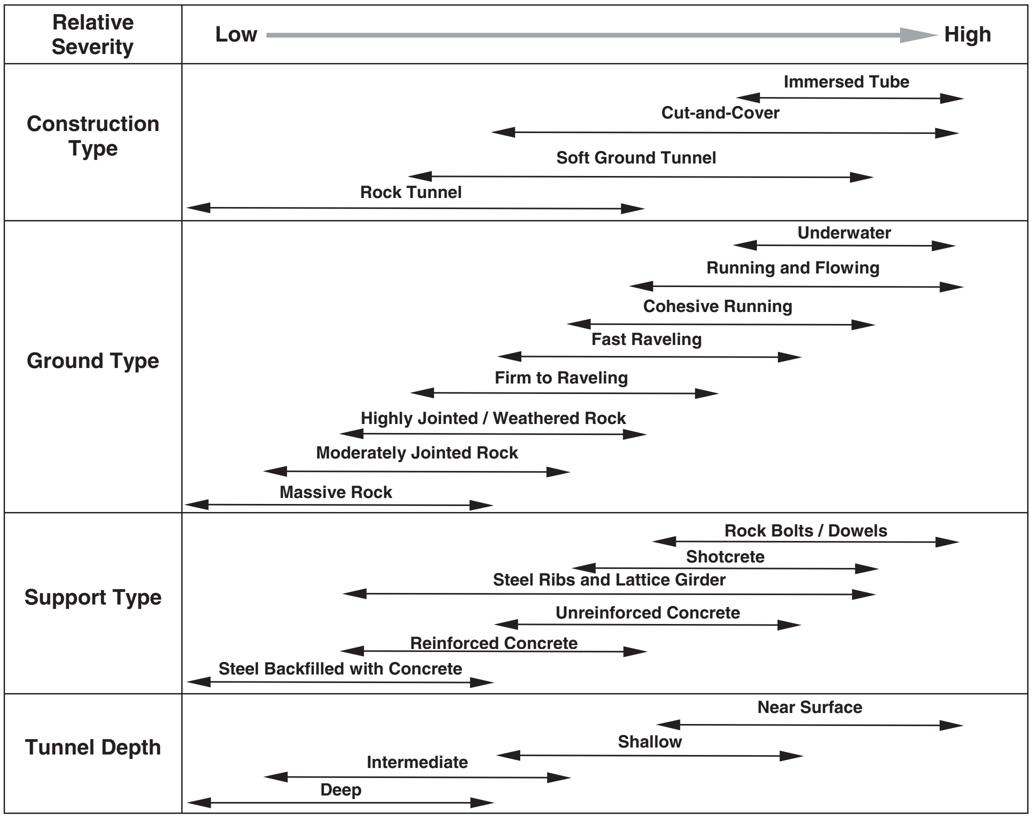
Table 12 presents relative severity ratings of tunnels based on some of the critical factors discussed above. The information in this table is based on recent tunnel security project experience and expert opinion. This chart has been prepared in a qualitative manner, and therefore should be used as such.

4.4.5 Damage Potential Rating of Tunnels

Based on the data and discussions presented herein, as well as the hazard and threat scenarios discussed in Chapter 2, Table 13 shows a damage potential rating chart for transportation tunnels. For rating purposes, the following primary hazards and threats were considered from the structural evaluation standpoint:

- Introduction of small IEDs, which are delivered via one to five aggressors transporting the payload in suitcase-type bags on foot and consolidating at a critical location inside the tunnel.
- Introduction of medium IEDs, which are delivered either by vehicle (car) or by multiple persons acting in concert to transport the payload and consolidating at a critical location inside the tunnel.
- Introduction of large IEDs, which are delivered either by vehicle (truck) or by multiple persons acting in concert to

Table 12. Relative severity ratings in transportation tunnels.



transport the payload and consolidating at a critical location inside the tunnel.

- Introduction of very large IEDs, which are delivered by ship, barge, or boat. The depth charge is dropped and detonated above an immersed tube tunnel.
- Fire load larger than 341 MBTU per hour (100 MW).

In addition to the size of the hazard or threat, other critical factors considered in the damage potential rating included type of tunnel construction, ground condition, ground support system, and soil or rock overburden thickness. The damage potential rating is divided into six categories—letters A through F—ranging from severely catastrophic (A) to negligible (F).

Tables 14, 15, and 16 present structural vulnerabilities to the most likely hazard or threat scenarios for road tunnels, transit tunnels, and rail tunnels, respectively. These tables basically combine the information given in Table 3 (hazard and threat scenarios) with the information given in Table 13 (damage potential ratings for transportation tunnels). The hazard and threat scenarios have been rearranged into subtables based on the "Path to Target" and the "Target." These items are located at the top left side of each subtable. The hazards and threats presented on the left side of the tables include very large, large, medium, and small IEDs and large fires. All of the hazards and threats were developed further to identify hazard and threat scenarios that include hazard and threat, path to target, tactical delivery device, and ultimate target. The right side of the tables contain each of the major tunnel types: immersed tube, cut-and-cover, bored or mined in soft to firm ground, bored or mined in strong rock, and air-rights structure tunnels. Each row represents a unique hazard or threat scenario. If that scenario poses danger to a certain type of tunnel, then that intersecting cell describes the physical vulnerability (PV), the operational vulnerability (OV) and the damage potential (DP). The damage potential is presented in terms of the rating abbreviations given in Table 13 (from A to F).

4.4.6 Summary

The information presented in Section 4.4 allows tunnel facility owners, operators, and engineers to conduct preliminary vulnerability rating assessments of their facilities and, if needed, to derive priority lists of tunnel structural components for further study.

4.5 System Elements and Vulnerabilities

4.5.1 Key Safety Functions

There are many systems serving transportation tunnels. Of these systems, many are not visible but are nonetheless

Table 13. Damage potential ratings for transportation tunnels.

Tunnel Type	Ground	Support System	Soil or Rock Overburden Thickness	Explosion			Fire (>34 MBTU per hour, or 100 MW)
				Small[1]	Medium[2]	Large[3]	
Bored or Mined	Strong Rock	All Types	< 1 x diameter	E	D	C	D
			> 1 x diameter	E	D	C	D
	Soft Rock/ Firm Ground	Rock Bolts with Wire Mesh/Lattice Girder/ Shotcrete	< 1 x diameter	D	B	B	B
			> 1 x diameter	D	B	B	B
		Steel Ribs with or without Liner Plate	< 1 x diameter	F	B	B	B
			>1 x diameter	F	B	B	B
		Cast-in-Place Concrete Liner	< 1 x diameter	F	B	B	C/B
			> 1 x diameter	F	C/B	B	C/B
		Segmental Concrete	< 1 x diameter	D	B	A	B
			> 1 x diameter	D	B	B/A	B
	Loose/Soft Ground	Steel Ribs or Lattice Girder with Shotcrete	< 1 x diameter	D	B	A	B
			>1 x diameter	D	B	A	B
		Cast-in-Place Concrete	< 1 x diameter	F	B	A	C/B
			> 1 x diameter	F	C/B	B/A	C/B
		Segmental Concrete	< 1 x diameter	D	B	A	B
			> 1 x diameter	D	B	A	B
Cut-and-Cover	Firm Ground	Unreinforced Concrete/Masonry Lining	< 15’	D	B	A	C
			> 15’	D	B	A	C
		Reinforced Concrete Lining	< 15’	D	B	A	C
			> 15’	D	B	A	C
	Loose/Soft Ground	Unreinforced Concrete/Masonry Lining	< 15’	D	B	A	C
			> 15’	D	B	A	C
		Reinforced Concrete Lining	< 15’	D	B	A	C
			> 15’	D	B	A	C
Immersed Tube		Steel Tube		D	B	A	D
		Concrete Tube		D	B	A	D
Air-Rights Structure				D	C	B	D

Notes:
1. Transported by foot.
2. Transported by car.
3. Transported by truck.

(continued on next page)

Table 13. (Continued).

Damage Potential	Definition
A = Severely Catastrophic	• Collapse—requires several months to 1 year to repair • Rapid flooding
B = Catastrophic	• Explosion - moderate to large area breach failure - potential flooding - facility closure over several weeks to months • Fire - significant liner damage (e.g., deep fire induced spalling through concrete liner; local failure of load carrying structural elements) - requires several weeks to months to repair
C = Critical	• Explosion - local breach failure - significant water inflow - requires a few days to weeks to repair • Fire - moderate liner damage (e.g., 6-inch [15-centimeter] fire induced concrete spalling; steel reinforcement exposed) - requires a few days to weeks to repair
D = Serious	• Explosion - local damage of liner—no breaching - controllable water inflow - repairable within 24 hours to a few days • Fire - local damage of liner (e.g., 2- to 3-inch [5- to 7.6-centimeter] fire induced concrete spalling) - repairable within 24 hours to a few days
E = Marginal	• Explosion - minor damage—spalling, cracking, lining overstress - repairable within 1 hour • Fire - minor damage (e.g., less than 1-inch [2.5-centimeter] fire induced concrete spalling) - repairable within 1 hour
F = Negligible	• Explosion - no damage • Fire - no damage

important to the ability of owners to effectively and safely operate any transportation tunnel. Systems serving transportation tunnels handle the following key safety functions:

- Emergency ventilation,
- Fire protection,
- Drainage,
- Power supply,
- Lighting,
- Signals,
- Train control,
- Traffic control,
- System control, and
- Communications.

4.5.2 Categorization of Systems

The systems serving the above key safety functions have been categorized into five primary categories to simplify the designation of critical elements:

- Ventilation
  – Emergency ventilation
- Life safety
  – Fire protection
  – Drainage
- Electrical
  – Primary
  – Ancillary
  – Traction
  – Emergency
- Command and Control
  – Traffic control
  – Train control
  – Signals
  – System control
- Communications

Ventilation includes all of the systems, equipment, and facilities required to provide ventilation of a tunnel during an emergency.

Table 14. Structural vulnerabilities to most likely hazard or threat scenarios for road tunnels.

Path to Target: Tunnel Roadway
Target: Tunnel Liner

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Cut-and-Cover Tunnel	Bored or Mined Tunnel	
						Soft to Firm Ground	Strong Rock
1H	Large IED	Truck	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	no inspections at portals to limit vehicle type, size, or cargo			
			DP	A	A	A-B	C
2H	Medium IED	Car/Van	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	no inspections at portals to limit vehicle type, size, or cargo			
			DP	B	B	B-C	D
3H	Small IED	Backpack	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	public access to roadway; inadequate surveillance			
			DP	D	D	D-F	E
4H	Large Fire[1]	Tanker	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	no vehicle inspections at portals to limit size, type, or cargo			
			DP	D	C	B-C	D

Path to Target: Tunnel Roadway
Target: Column/Wall/Roof Slab

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Air-Rights Structure
5H	Large IED	Truck	**PV**	insufficient protection of column, wall, or roof slab; relative proximity of threat to column, wall, or roof slab
			OV	no inspections at entrances to limit vehicle type, size, or cargo
			DP	B
6H	Medium IED	Car/Van	**PV**	insufficient protection of column/wall/roof slab; relative proximity of threat to column/wall/roof slab
			OV	no inspections at entrances to limit vehicle type, size, or cargo
			DP	C
7H	Small IED	Backpack	**PV**	insufficient protection of column/wall/roof slab; relative proximity of threat to column/wall/roof slab
			OV	public access to roadway; inadequate surveillance
			DP	D
8H	Large Fire[1]	Tanker	**PV**	insufficient fire protection of column/wall/roof slab
			OV	no vehicle inspections at entrances to limit size, type, or cargo
			DP	C

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential

Note:
1 . More than 341 MBTU per hour (100 MW)

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Table 14. (Continued).

Path to Target: Tunnel Roadway
Target: Portal

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Air-Rights Structure	Immersed Tube Tunnel	Cut-and-Cover Tunnel	Bored or Mined Tunnel	
							Soft to Firm Ground	Strong Rock
9H	Large Fire[1]	Tanker	PV	insufficient portal strength				
			OV	no vehicle inspections at portals to limit size, type, or cargo				
			DP	C	D	C	B-C	D

Path to Target: Waterway
Target: Portal or Shaft Wall

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Bored or Mined Tunnel	
					Soft to Firm Ground	Strong Rock
10H	Very Large IED	Depth Charge or Ship	PV	insufficient portal or shaft wall strength		
			OV	uncontrolled ship traffic movement through channel over tunnel with uninspected cargo		
			DP	A	A	A

Path to Target: Waterway
Target: Top of Tunnel

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Bored or Mined Tunnel	
					Soft to Firm Ground	Strong Rock
11H	Very Large IED	Depth Charge from Ship	PV	insufficient roof slab thickness; inadequate tunnel cover		
			OV	uncontrolled ship traffic movement through channel over tunnel with uninspected cargo		
			DP	A	A	C

Path to Target: Surface Roadway over Tunnel
Target: Roof Slab

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Cut-and-Cover Tunnel	Air-Rights Structure
12H	Large IED	Truck	PV	insufficient roof slab thickness; inadequate tunnel cover	
			OV	if parking structure, no vehicle inspections to limit size, type, or cargo	
			DP	A	A
13H	Medium IED	Truck or Multiple Backpacks	PV	insufficient roof slab thickness; inadequate tunnel cover	
			OV	if parking structure, no vehicle inspections to limit size, type, or cargo	
			DP	B	B

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential

Note:
1. More than 341 MBTU per hour (100 MW)

Table 15. Structural vulnerabilities to most likely hazard or threat scenarios for transit tunnels.

Path to Target: Trackway
Target: Tunnel Liner

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Cut-and-Cover Tunnel	Bored or Mined Tunnel	
						Soft to Firm Ground	Strong Rock
1T	Large IED	Transit Car/ Engine	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	insufficient inspection in rail yards and shops			
			DP	A	A	A-B	C
2T	Medium IED	Transit Car/ Engine or Multiple Backpacks	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	insufficient inspection in rail yards and shops; uncontrolled access through ancillary facilities (i.e., stations, exits/stairs)			
			DP	B	B	B-C	D
3T	Small IED	Backpack	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	insufficient inspection in rail yards and shops; uncontrolled access through ancillary facilities (i.e., stations, exits/stairs); inadequate surveillance			
			DP	D	D	D-F	E
4T	Large Fire[1]	IED on Transit Vehicle	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	insufficient inspection in rail yards and shops			
			DP	D	C	B-C	D

Path to Target: Trackway
Target: Column/Wall/Roof Slab

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Air-Rights Structure
5T	Large IED	Transit Car/ Engine	**PV**	insufficient protection of column/wall/roof slab; relative proximity of threat to column/wall/roof slab
			OV	insufficient inspection in rail yards and shops
			DP	B
6T	Medium IED	Transit Car/ Engine or Multiple Backpacks	**PV**	insufficient protection of column/wall/roof slab; relative proximity of threat to column/wall/roof slab
			OV	insufficient inspection in rail yards and shops; uncontrolled access through ancillary facilities (i.e., stations, exits/stairs)
			DP	C
7T	Small IED	Backpack	**PV**	insufficient protection of column/wall/roof slab; relative proximity of threat to column/wall/roof slab
			OV	insufficient inspection in rail yards and shops; uncontrolled access through ancillary facilities (i.e., stations, exits/stairs); inadequate surveillance
			DP	D
8T	Large Fire[1]	IED on Transit Vehicle	**PV**	insufficient fire protection of column/wall/roof slab
			OV	insufficient inspection in rail yards and shops
			DP	C

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential

Note:
1. More than 341 MBTU per hour (100 MW)

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Table 15. (Continued).

Path to Target: Trackway
Target: Portal

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Air-Rights Structure	Immersed Tube Tunnel	Cut-and-Cover Tunnel	Bored or Mined Tunnel	
							Soft to Firm Ground	Strong Rock
9T	Large Fire[1]	IED on Transit Vehicle	**PV**	insufficient portal strength				
			OV	insufficient inspection in rail yards and shops; uncontrolled access to rail cars and engines; no cargo restrictions; insufficient inspection of cargo containers at origin				
			DP	C	D	C	B-C	D

Path to Target: Waterway
Target: Portal or Shaft Wall

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Bored or Mined Tunnel	
					Soft to Firm Ground	Strong Rock
10T	Very Large IED	Depth Charge or Ship	**PV**	insufficient portal or shaft wall strength		
			OV	uncontrolled ship traffic movement through channel over tunnel with uninspected cargo		
			DP	A	A	A

Path to Target: Waterway
Target: Top of Tunnel

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Bored or Mined Tunnel	
					Soft to Firm Ground	Strong Rock
11T	Very Large IED	Depth Charge from Ship	**PV**	insufficient roof slab thickness; inadequate tunnel cover		
			OV	uncontrolled ship traffic movement through channel over tunnel with uninspected cargo		
			DP	A	A	C

Path to Target: Surface Roadway over Tunnel
Target: Roof Slab

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Cut-and-Cover Tunnel	Air-Rights Structure
12T	Large IED	Truck	**PV**	insufficient roof slab thickness; inadequate tunnel cover	
			OV	no vehicle inspections to limit size, type, or cargo	
			DP	A	A
13T	Medium IED	Truck or Multiple Backpacks	**PV**	insufficient roof slab thickness; inadequate tunnel cover	
			OV	no vehicle inspections to limit size, type, or cargo	
			DP	B	B

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential

Note:
1. More than 341MBTU per hour (100 MW)

Table 16. Structural vulnerabilities to most likely hazard or threat scenarios for rail tunnels.

Path to Target: Trackway
Target: Tunnel Liner

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Cut-and-Cover Tunnel	Bored or Mined Tunnel	
						Soft to Firm Ground	Strong Rock
1R	Large IED	Rail Car/ Engine	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	insufficient inspection in rail yards and shops			
			DP	A	A	A-B	C
2R	Medium IED	Rail Car/ Engine or Multiple Backpacks	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	insufficient inspection in rail yards and shops; uncontrolled access through ancillary facilities (i.e., stations, exits/stairs)			
			DP	B	B	B-C	D
3R	Small IED	Backpack	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	insufficient inspection in rail yards and shops; uncontrolled access through ancillary facilities (i.e., stations, exits/stairs)			
			DP	D	D	D-F	E
4R	Large Fire[1]	IED on Rail Vehicle	**PV**	insufficient liner thickness; relative proximity of threat to liner			
			OV	insufficient inspection in rail yards and shops			
			DP	D	C	B-C	D

Path to Target: Trackway
Target: Column/Wall/Roof Slab

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Air-Rights Structure
5R	Large IED	Rail Car/ Engine	**PV**	insufficient protection of column/wall/roof slab; relative proximity of threat to column/wall/roof slab
			OV	insufficient inspection in rail yards and shops
			DP	B
6R	Medium IED	Rail Car/ Engine	**PV**	insufficient protection of column/wall/roof slab; relative proximity of threat to column/wall/roof slab
			OV	insufficient inspection in rail yards and shops; uncontrolled access through ancillary facilities (i.e., stations, tunnel exits/stairs)
			DP	C
7R	Small IED	Backpack	**PV**	insufficient protection of column/wall/roof slab; relative proximity of threat to column/wall/roof slab
			OV	insufficient inspection in rail yards and shops; uncontrolled access through ancillary facilities (i.e., stations, tunnel exits/stairs); inadequate surveillance
			DP	D
8R	Large Fire[1]	IED on Rail Vehicle	**PV**	insufficient fire protection of column/wall/roof slab
			OV	insufficient inspection in rail yards and shops
			DP	C

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential

Note:
1. More than 341 MBTU per hour (100 MW)

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Table 16. (Continued).

Path to Target: Trackway
Target: Portal

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Air-Rights Structure	Immersed Tube Tunnel	Cut-and-Cover Tunnel	Bored or Mined Tunnel	
							Soft to Firm Ground	Strong Rock
9R	Large Fire[1]	IED on Rail Vehicle	**PV**	insufficient portal strength				
			OV	insufficient inspection in rail yards and shops; uncontrolled access to rail cars and engines; no cargo restrictions; insufficient inspection of cargo containers at origin				
			DP	C	D	C	B-C	D

Path to Target: Waterway
Target: Portal or Shaft Wall

Scenario No.	Hazard and Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Bored or Mined Tunnel	
					Soft to Firm Ground	Strong Rock
10R	Very Large IED	Depth Charge or Ship	**PV**	insufficient portal or shaft wall strength		
			OV	uncontrolled ship traffic movement through channel over tunnel with uninspected cargo		
			DP	A	A	A

Path to Target: Waterway
Target: Top of Tunnel

Scenario No.	Hazard and Threat	Tactical Delivery Device	PV/OV/DP	Immersed Tube Tunnel	Bored or Mined Tunnel	
					Soft to Firm Ground	Strong Rock
11R	Very Large IED	Depth Charge from Ship	**PV**	insufficient roof slab thickness; inadequate tunnel cover		
			OV	uncontrolled ship traffic movement through channel over tunnel with uninspected cargo		
			DP	A	A	C

Path to Target: Surface Roadway over Tunnel
Target: Roof Slab

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Cut-and-Cover Tunnel	Air-Rights Structure
12R	Large IED	Truck	**PV**	insufficient roof slab thickness; inadequate tunnel cover	
			OV	no vehicle inspections to limit size, type, or cargo	
			DP	A	A
13R	Medium IED	Truck or Multiple Backpacks	**PV**	insufficient roof slab thickness; inadequate tunnel cover	
			OV	no vehicle inspections to limit size, type, or cargo	
			DP	B	B

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential

Note:
1. More than 341 MBTU per hour (100 MW)

Life safety includes all of the systems, equipment, and facilities required to provide protection during an emergency to the tunnel and its inhabitants.

Electrical includes both normal and emergency power for ancillaries, systems, and train traction.

Command and control includes traffic, train, and system control, along with signals.

Communications includes all communications systems required to make the tunnel functional and safe.

To create the above five primary categories of systems, the research team started with an initial list of safety systems serving road, transit, and rail tunnels. Table 17 shows this initial list of safety systems, along with the tunnel functions associated with each system. After careful review of the data in this table, the research team made several decisions. One decision was to combine the categories of passenger rail tunnels and freight rail tunnels in this report because the vulnerabilities and damage potentials are similar. The other decisions involve the elimination of some elements (such as emission control, emission monitoring, and normal lighting) because they do not affect the vulnerability of particular tunnels. In the end, the research team decided on the above five primary categories of systems. These revised primary categories are depicted in Table 18.

4.5.3 Degree of Impact on Safety and Operations

When systems are disrupted, the degree of impact on the safety and operations of the tunnel can vary. Table 19 provides a subjective evaluation of the different impacts and mitigation requirements. This evaluation is consistent with the FTA's ranking system [Ref. 20].

System paralysis can occur if a coordinated attack is aimed at specifically related systems. For example, if a multiple-point attack focuses on the electrical power supply as well as any emergency backup systems and is successful, most of the tunnel's MEC systems will be disabled. Such threats may cause synergistic effects and may require systemwide checks to be conducted before tunnel operations are resumed.

Tables 20, 21, and 22 subjectively highlight the impact of system element disruption on each of the transportation tunnel function types. These subjective impact ratings are based on single-point attacks. In the case of multiple-point or coordinated attacks, the disruption to the tunnel systems would obviously become more severe.

4.5.4 Potentially Critical Locations

A careful assessment of the potentially critical locations was made for each tunnel function type. This assessment was combined with the system element impact list to develop the draft guidelines. The results of the combined assessment and list are presented in Table 23 as a list of potentially critical locations where each of the tunnel systems is vulnerable. The table records the level of vulnerability as "Low," "Medium," or "High."

Table 24 estimates the vulnerabilities of critical locations.

Tables 25, 26, and 27 present system vulnerabilities to the most likely hazard or threat scenarios for road tunnels, transit tunnels, and rail tunnels, respectively. These tables combine the information given in Table 3 (hazard and threat scenarios) with the information given in Table 24 (vulnerabilities of critical locations). The hazard and threat scenarios have been rearranged into subtables on the basis of the "Path to Target" as well as the "Target." These items are located at the top left side of each subtable. The hazards and threats presented on the left side of the tables include the introduction to the tunnel property of large, medium, and small IEDs; large fires; hazardous materials; C/B/R; and cyber attack. All of the hazards and threats were developed further to identify scenarios that include hazard or threat, path to target, tactical delivery device, and ultimate target. Each of the hazard or threat scenarios was considered for each of the five primary system categories presented in Section 4.5.2. Each row presents a unique set of vulnerabilities (both physical and operational) and a set of damage potentials. This should provide the owner or operator with a clear guide to the types of hazard and threat scenarios possible for tunnels.

4.5.5 Summary

Nonstructural (i.e., tunnel systems) guidelines have been developed to provide the owner or operator with a simple method to identify the critical elements and locations within his or her tunnel based on the hazard or threat, path to target, tactical delivery device, and ultimate target. Each of the critical systems has been assessed, and a set of vulnerabilities and damage potentials have been identified for each reasonable hazard or threat.

4.6 Chapter Summary

The information presented in this chapter allows tunnel facility owners, operators, and engineers to conduct preliminary vulnerability rating (i.e., screening) assessments of their facilities and, if needed, to derive priority lists of a tunnel's structural components and system components for further study.

To determine the countermeasures available to the tunnel owner or operator, the research team applied comparative analysis to the hazard and threat scenarios to discern common themes. From this analysis, it was determined that the

Table 17. Initial categories of safety systems.

Safety System		Tunnel Function			
		Road	Transit	Freight Rail	Passenger Rail
Ventilation System Type	Transverse Ventilation	●			
	Longitudinal Ventilation	●	●	●	●
Ventilation System Facilities	Ventilation Buildings	●			
	Ventilation Shafts	●	●		
	Vent Ducts (Transverse)	●			
	Intake Louvers	●	●	●	●
Ventilation System Equipment	Central Fans (Transverse)	●			
	Jet Fans (Longitudinal)	●	●		
	Shaft Fans (Longitudinal)	●	●		
Ventilation System Function	Emissions Control	●		●	
	Smoke Management	●	●	●	●
Plumbing	Drainage	●	●	●	●
Life Safety Systems	Fire/Smoke Detection	●	Note 1		Note 1
	Fire Standpipe/Hydrants	●	●	●	●
	Fire Apparatus	●			
	Portable Fire Extinguishers	●	●	●	●
	Fixed Fire Suppression[2]	Notes 3 & 4	Notes 5 & 6		Note 6
	Emergency Exits	●	●	●	●
	Cross Passages	●	●	●	●
	CCTV[8]	●			
Electrical Power	Auxiliary Power	●	●	●	●
	Traction Power[7]		●		●
	Emergency Power	●	●	●	●
Lighting Systems	Normal Lighting	●			
	Emergency Lighting	●	●	●	●
Signal	Train Signals		●	●	●
	Traffic Signals	●			
Communications	Emergency Phones	●	●	●	●
	SCADA[8]/Data	●	●	●	●
	Control Center	●	●	●	●
Control Systems	Automatic	●	●	●	●
	On-Site	●	●	●	●
	Remote	●	●	●	●
	Emissions Monitoring	●			

Notes:
1. Fire/smoke detection are only in stations and ancillary facilities.
2. This category includes all fixed fire suppression systems such as sprinklers, mist, and deluge systems.
3. Fixed fire suppression systems are only in ancillary facilities.
4. There are three road tunnels in the United States with sprinkler systems in the roadway.
5. There are some U.S. transit stations with under-car sprinkler systems on tracks.
6. Fixed fire suppression systems are only in stations and ancillary facilities.
7. Traction power is in all transit and rail tunnels with electrified train vehicles.
8. CCTV = closed-circuit television; SCADA = supervisory control and data acquisition.

Table 18. Revised categories of safety systems.

Safety System		Tunnel Function: Road	Tunnel Function: Transit	Tunnel Function: Rail
Ventilation				
Ventilation Type	Transverse Ventilation	●		
	Longitudinal Ventilation	●	●	●
Ventilation Facilities	Ventilation Buildings	●		
	Ventilation Shafts	●	●	
	Vent Ducts (Transverse)	●		
	Air Intakes	●	●	●
Ventilation Equipment	Central Fans (Transverse)	●		
	Jet Fans (Longitudinal)	●	●	
	Shaft Fans (Longitudinal)	●	●	
Ventilation Function	Smoke Management	●	●	●
Life Safety				
Drainage	Drainage	●	●	●
Fire Protection	Fire/Smoke Detection	●	Note 1	Note 1
	Fire Standpipe/Hydrants	●	●	●
	Fire Apparatus	●		
	Portable Fire Extinguishers	●	●	●
	Fixed Fire Suppression[2]	Notes 3 & 4	Notes 5 & 6	Note 6
	Emergency Exits	●	●	●
	Cross Passages	●	●	●
	CCTV[8]	●		
Electrical				
Power	Ancillary Power	●	●	●
	Traction Power[7]		●	●
	Emergency Power	●	●	●
Lighting	Emergency Lighting	●	●	●
Command and Control				
Control	Train Control		●	●
	Traffic Control	●		
	System Control	●	●	●
	Signals	●	●	●
	SCADA[8]/Data	●	●	●
	Command and Control Center	●	●	●
Communications				
Communications	Emergency Telephones	●	●	●

Notes:
1. Fire/smoke detection are only in stations and ancillary facilities.
2. This category includes all fixed fire suppression systems such as sprinklers, mist, and deluge systems.
3. Fixed fire suppression systems are only in ancillary facilities.
4. There are three road tunnels in the United States with sprinkler systems in the roadway.
5. There are some U.S. transit stations with under-car sprinkler systems on tracks.
6. Fixed fire suppression systems are only in stations and ancillary facilities.
7. Traction power is in all transit and rail tunnels with electrified train vehicles.
8. CCTV = closed-circuit television; SCADA = supervisory control and data acquisition.

Table 19. Degree of impact on safety and operations.

Impact Rating	Life Safety	Tunnel Operations	Operation Restoration
Severely Catastrophic	Incident impacts life safety sufficiently to require tunnel closure	Incident impacts tunnel operations sufficiently to require complete shutdown	Incident impacts operation restoration, taking several months to 1 year
Catastrophic	Incident impacts life safety sufficiently to require tunnel closure	Incident impacts tunnel operations sufficiently to require complete shutdown	Incident impacts operation restoration, taking several weeks to months
Critical	Incident impacts life safety	Incident impacts tunnel operations sufficiently to require a disruption of operations	Incident impacts operation restoration, taking a few days to weeks
Serious	Incident impacts life safety	Incident impacts tunnel operations sufficiently to require a disruption of operations	Incident impacts operation restoration, taking 24 hours to a few days
Marginal	Incident impacts life safety	Incident impacts tunnel operations sufficiently to require a modest disruption of operations	Incident impacts operation restoration, taking less than 1 hour
Negligible	Incident does not impact life safety	Incident does not impact tunnel operations	Incident does not impact operation restoration

basic platforms for disruption emanated from four major categories of sources:

- Large fires;
- Explosive devices;
- Hazardous materials, including chemical/biological/radiological (C/B/R) agents; and
- Cyber attacks.

The research team then analyzed the damage potential of a disturbance emanating from each of the four major categories of sources. Damage is the loss of use of the tunnel. Minor damage may result from a disabled car blocking one lane, and major damage may result from a fire that closes the tunnel to traffic. The scope of the functional loss is significant, and the damage potential reflects the potential percentage loss of the tunnel use. The percentage loss of the tunnel use is important, more so than the hazard or threat that triggered the incident. Given this importance, the research team began to match the greatest damage potential, or potential loss of use of the tunnel, to the hazards and threats. The research team finally summarized the hazards and threats that have the greatest damage potential, or the potential for total loss of tunnel use.

Large fires and explosive devices had a similar damage potential as that of all other hazards and threats examined. Fire, as a primary or secondary hazard (i.e., accidental combustion) or threat (i.e., arson) can cause severe damage to the tunnel because of closure. An explosion can cause similar disruption to the tunnel. Each of these main hazards and threats exhibited damage potential to both the structure and systems of the tunnel.

Therefore, the hazard and threat platforms were fully described as a series of scenarios, including the type and size of hazard or threat, the tactical delivery device, and the targeted tunnel element. A lengthy list of scenarios was compressed to reflect the common hazard and threat platforms. The vulnerabilities of various tunnel types to these hazard and threat scenarios, as well as the relative damage potential, appear in Tables 14, 15, and 16 for road, transit, and rail tunnels, respectively. The vulnerabilities of various tunnel safety system types to the same set of hazard and threat scenarios, along with relative damage potentials, appear in Tables 25, 26, and 27 for road, transit, and rail tunnels, respectively. These tables present the groundwork for the presentation of countermeasures, which is discussed in the next chapter.

Table 20. Disruptive impacts in road tunnels.

Safety System		Life Safety	Tunnel Operations	Operation Restoration
Ventilation				
System Type	Transverse Ventilation	Catastrophic	Catastrophic	Catastrophic
	Longitudinal Ventilation	Catastrophic	Catastrophic	Catastrophic
Facilities	Ventilation Buildings	Catastrophic	Catastrophic	Catastrophic
	Ventilation Shafts	Catastrophic	Catastrophic	Catastrophic
	Vent Ducts (Transverse)	Catastrophic	Catastrophic	Catastrophic
	Air Intakes	Catastrophic	Catastrophic	Catastrophic
Equipment	Central Fans (Transverse)	Catastrophic	Catastrophic	Catastrophic
	Jet Fans (Longitudinal)	Catastrophic	Catastrophic	Catastrophic
	Shaft Fans (Longitudinal)	Catastrophic	Catastrophic	Catastrophic
System Function	Smoke Management	Catastrophic	Catastrophic	Catastrophic
Life Safety				
Systems	Fire/Smoke Detection	Catastrophic	Catastrophic	Catastrophic
	CCTV	Critical	Critical	Catastrophic
	Fire Standpipe/Hydrants	Catastrophic	Catastrophic	Catastrophic
	Fire Apparatus	Critical	Serious	Critical
	Portable Fire Extinguishers	Critical	Marginal	Critical
	Fixed Fire Suppression	Catastrophic	Catastrophic	Catastrophic
	Drainage	Critical	Critical	Catastrophic
Facilities	Emergency Exits	Catastrophic	Catastrophic	Catastrophic
	Cross Passages	Catastrophic	Catastrophic	Catastrophic
Electrical				
Power	Auxiliary Power	Catastrophic	Catastrophic	Catastrophic
	Traction Power	- - - - -	- - - - -	- - - - -
	Emergency Power	Catastrophic	Catastrophic	Catastrophic
Lighting	Emergency Lighting	Critical	Critical	Critical
Command and Control				
Command and Control	Train Control	- - - - -	- - - - -	- - - - -
	Traffic Control	Catastrophic	Catastrophic	Catastrophic
	System Control	Catastrophic	Catastrophic	Catastrophic
	Signals	Catastrophic	Catastrophic	Catastrophic
	SCADA/Data	Critical	Critical	Critical
	Command and Control Center	Catastrophic	Catastrophic	Catastrophic
Communications				
Communications	Emergency Phones	Catastrophic	Critical	Critical

CCTV = closed-circuit television; SCADA = supervisory control and data acquisition; dashes = data not available.

Table 21. Disruptive impacts in transit tunnels.

Safety System		Life Safety	Tunnel Operations	Operation Restoration
Ventilation				
System Type	Transverse Ventilation	- - - - -	- - - - -	- - - - -
	Longitudinal Ventilation	Catastrophic	Catastrophic	Catastrophic
Facilities	Ventilation Structures	Catastrophic	Catastrophic	Catastrophic
	Ventilation Shafts	Catastrophic	Catastrophic	Catastrophic
	Vent Ducts (Transverse)	Catastrophic	Catastrophic	Catastrophic
	Air Intakes	Catastrophic	Catastrophic	Catastrophic
Equipment	Central Fans (Transverse)	- - - - -	- - - - -	- - - - -
	Jet Fans (Longitudinal)	Catastrophic	Catastrophic	Catastrophic
	Shaft Fans (Longitudinal)	Catastrophic	Catastrophic	Catastrophic
System Function	Smoke Management	Catastrophic	Catastrophic	Catastrophic
Life Safety				
Systems	Fire/Smoke Detection	Catastrophic	Critical	Critical
	CCTV	Critical	Critical	Critical
	Fire Standpipe/Hydrants	Catastrophic	Catastrophic	Catastrophic
	Fire Apparatus	Critical	Serious	Serious
	Portable Fire Extinguishers	Marginal	Negligible	Negligible
	Fixed Fire Suppression	Critical	Serious	Serious
	Drainage	Marginal	Marginal	Critical
Facilities	Fixed Fire Suppression	Critical	Serious	Serious
	Emergency Exits	Catastrophic	Critical	Catastrophic
	Cross Passages	Catastrophic	Critical	Catastrophic
Electrical				
Power	Primary Power	Catastrophic	Catastrophic	Catastrophic
	Auxiliary Power	Critical	Critical	Critical
	Traction Power	Catastrophic	Catastrophic	Catastrophic
	Emergency Power	Catastrophic	Catastrophic	Catastrophic
Lighting	Emergency Lighting	Critical	Serious	Serious
Command and Control				
Command and Control	Train Control	Catastrophic	Critical	Critical
	Traffic Control	- - - - -	- - - - -	- - - - -
	System Control	Catastrophic	Catastrophic	Catastrophic
	Signals	Catastrophic	Catastrophic	Catastrophic
	SCADA/Data	Critical	Serious	Serious
	Command and Control Center	Catastrophic	Critical	Critical
Communications				
Communications	Emergency Phones	Catastrophic	Serious	Serious

CCTV = closed-circuit television; SCADA = supervisory control and data acquisition; dashes = data not available.

Table 22. Disruptive impacts in rail tunnels.

Safety System		Life Safety	Tunnel Operations	Operation Restoration
Ventilation				
System Type	Transverse Ventilation	- - - - -	- - - - -	- - - - -
	Longitudinal Ventilation	Catastrophic	Catastrophic	Catastrophic
Facilities	Ventilation Structures	Catastrophic	Catastrophic	Catastrophic
	Ventilation Shafts	Catastrophic	Catastrophic	Catastrophic
	Vent Ducts (Transverse)	Catastrophic	Catastrophic	Catastrophic
	Intake Louvers	Catastrophic	Catastrophic	Catastrophic
Equipment	Central Fans (Transverse)	- - - - -	- - - - -	- - - - -
	Jet Fans (Longitudinal)	Catastrophic	Catastrophic	Catastrophic
	Shaft Fans (Longitudinal)	Catastrophic	Catastrophic	Catastrophic
System Function	Smoke Management	Catastrophic	Catastrophic	Catastrophic
Life Safety				
Systems	Fire/Smoke Detection	Serious	Serious	Critical
	CCTV	Serious	Serious	Critical
	Fire Standpipe/Hydrants	Critical	Critical	Critical
	Fire Apparatus	Critical	Serious	Critical
	Portable Fire Extinguishers	Negligible	Negligible	Negligible
	Fixed Fire Suppression	Negligible	Negligible	Negligible
	Drainage	Marginal	Critical	Critical
Facilities	Emergency Exits	Serious	Serious	Serious
	Cross Passages	Serious	Serious	Serious
Electrical				
Power	Primary Power	Catastrophic	Catastrophic	Catastrophic
	Auxiliary Power	Catastrophic	Catastrophic	Catastrophic
	Traction Power	Catastrophic	Catastrophic	Catastrophic
	Emergency Power	Catastrophic	Catastrophic	Catastrophic
Lighting	Emergency Lighting	Marginal	Marginal	Marginal
Command and Control				
Command and Control	Train Control	Catastrophic	Catastrophic	Critical
	Traffic Control	- - - - -	- - - - -	- - - - -
	System Control	Catastrophic	Catastrophic	Catastrophic
	Signals	Catastrophic	Catastrophic	Catastrophic
	SCADA/Data	Critical	Serious	Serious
	Command and Control Center	Catastrophic	Catastrophic	Catastrophic
Communications				
Communications	Emergency Phones	Critical	Marginal	Marginal

CCTV = closed-circuit television; SCADA = supervisory control and data acquisition; dashes = data not available.

Table 23. Vulnerabilities of potentially critical locations.

Critical System	Critical Location	Tunnel Function		
		Road Tunnel	Transit Tunnel	Rail Tunnel
Ventilation	Tunnel	Low	Low	Low
	Portals	Low	Low	Low
	Ventilation Structures	High	High	High
	Ventilation Shafts	High	High	Medium
	Stations	-------	High	High*
	Ventilation Ducts	High	Low	Low
	Control Center	High	High	High
	Utilities	High	High	High
Fire Protection	Tunnel	Medium	Low	Low
	Portals	Low	Low	Low
	Ventilation Structures	Medium	Medium	Medium
	Ventilation Shafts	Low	Medium	Medium
	Stations	-------	High	High*
	Ventilation Ducts	Low	Low	Low
	Control Center	Medium	Medium	Medium
	Utilities	High	High	High
Drainage	Tunnel	High	Medium	Medium
	Portals	Medium	Low	Low
	Ventilation Structures	Low	Medium	Medium
	Ventilation Shafts	Low	Low	Low
	Ventilation Ducts	Medium	Low	Low
	Stations	-------	Low	Low*
	Control Center	Low	Low	Low
	Utilities	High	High	High
Electrical	Tunnel	High	High	High
	Portals	Medium	Medium	Medium
	Ventilation Structures	High	High	High
	Ventilation Shafts	Low	Low	Low
	Ventilation Ducts	Low	Low	Low
	Stations	-------	High	High*
	Control Center	High	High	High
	Utilities	High	High	High
Communications	Tunnel	High	High	High
	Portals	Low	Low	Low
	Ventilation Structures	Low	Low	Low
	Ventilation Shafts	Low	Low	Low
	Ventilation Ducts	Low	Low	Low
	Stations	-------	High	High*
	Control Center	High	High	High
	Utilities	High	High	High
Command and Control	Tunnel	High	High	High
	Portals	High	High	High
	Ventilation Structures	Low	Low	Low
	Ventilation Shafts	Low	Low	Low
	Ventilation Ducts	Low	Low	Low
	Stations	-------	High	High*
	Control Center	High	High	High
	Utilities	High	High	High

* Stations only in passenger rail tunnels.

Table 24. Vulnerabilities of critical locations.

Critical Location	Critical System or Element	Primary Hazard or Threat						
		Large IED	Medium IED	Small IED	Large Fire	Hazardous Materials	C/B/R	Cyber Attack
Tunnel Shell	Ventilation	F	F	F	F	D	F	F
	Life Safety	F	F	F	E	D	F	D
	Electrical	C	C	C	D	D	F	D
	Command and Control	C	C	C	F	D	F	D
	Communications	C	C	C	D	D	F	D
Portals	Ventilation	F	F	F	F	D	F	F
	Life Safety	F	F	F	E	D	F	D
	Electrical	C	C	C	D	D	F	D
	Command and Control	C	C	C	F	D	F	D
	Communications	C	C	C	D	D	F	D
Ventilation Structures	Ventilation	B	B	C	B	D	C	D
	Life Safety	B	B	C	B	D	C	D
	Electrical	B	B	C	C	D	C	D
	Command and Control	B	B	C	C	D	C	B
	Communications	B	B	C	C	D	C	D
Ventilation Shafts	Ventilation	B	B	C	B	D	B	B
	Life Safety	C	C	D	B	D	C	D
	Electrical	C	C	D	C	D	C	D
	Command and Control	C	C	D	B	D	C	D
	Communications	C	C	D	B	D	C	D
Ventilation Ducts	Ventilation	C	C	B	B	D	B	B
	Life Safety	D	D	C	C	D	C	D
	Electrical	D	D	C	C	D	C	D
	Command and Control	D	D	C	B	D	C	D
	Communications	D	D	C	B	D	C	D
Stations	Ventilation	B	B	C	C	D	B	B
	Life Safety	B	B	C	B	D	C	C
	Electrical	B	B	C	E	D	C	C
	Command and Control	B	B	C	C	D	C	C
	Communications	B	B	C	B	D	C	D
Control Centers	Ventilation	B	B	C	C	D	C	B
	Life Safety	B	B	C	C	D	C	C
	Electrical	B	B	C	C	D	C	C
	Command and Control	B	B	C	B	D	C	B
	Communications	B	B	C	B	D	C	B
Substation	Ventilation	C	C	C	D	D	C	F
	Life Safety	C	C	C	D	D	C	F
	Electrical	B	B	B	D	D	C	F
	Command and Control	B	B	B	D	D	C	F
	Communications	B	B	B	D	D	C	F

A = Severely Catastrophic
B = Catastrophic
C = Critical
D = Serious
E = Marginal
F = Negligible

Table 25. Vulnerabilities to most likely hazard and threat scenarios for road tunnels.

Path to Target: Surface Access Roadway
Target: Stand-Alone Command and Control (C&C) Center

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
14H	Large IED	Truck	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	N/A	N/A	N/A	total loss	total loss
15H	Medium IED	Car/Van	**PV**	Insufficient perimeter protection				
			OV	Insufficient surveillance				
			DP	N/A	N/A	N/A	total loss	total loss
16H	Small IED	Backpack[2]	**PV**	Insufficient perimeter protection				
			OV	Insufficient surveillance				
			DP	N/A	N/A	N/A	total loss	total loss

Path to Target: Surface Access Roadway
Target: Stand-Alone Substation

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
17H	Large IED	Truck	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	N/A	N/A	total loss[8]	N/A	N/A
18H	Medium IED	Car/Van	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	partial loss[8]	N/A	N/A
19H	Small IED	Backpack[2]	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	total loss[8]	N/A	N/A

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

Table 25. (Continued).

Path to Target: Surface Access Roadway
Target: Ventilation Structure[3]

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
20H	Large IED	Truck	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	total loss	total loss	total loss[8]	total loss	total loss
21H	Medium IED	Car/Van	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	partial loss	total loss	partial loss[8]	partial loss	partial loss
22H	Small IED	Backpack[2]	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	partial loss	total loss	partial loss[8]	partial loss	partial loss

Path to Target: Tunnel Roadway
Target: C&C Center Above or Adjacent to the Tunnel

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
23H	Large IED	Truck	**PV**	accessibility via public tunnel				
			OV	no vehicle inspections at portals				
			DP	N/A	N/A	N/A	total loss	total loss
24H	Medium IED	Car/Van	**PV**	accessibility via public tunnel				
			OV	no vehicle inspections at portals				
			DP	N/A	N/A	N/A	partial loss	partial loss

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

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Table 25. (Continued).

Path to Target: Tunnel Roadway
Target: Ventilation Structure Above or Adjacent to the Tunnel[3]

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
25H	Large IED	Truck	**PV**	ventilation shafts and ducts provide a clear path for blast wave to propagate from tunnel to ventilation building				
			OV	no vehicle inspections at portals				
			DP	total loss	total loss	total loss[8]	total loss	total loss
26H	Medium IED	Car/Van	**PV**	ventilation shafts and ducts provide a clear path for blast wave to propagate from tunnel to ventilation building				
			OV	no vehicle inspections at portals				
			DP	total loss	total loss	total loss[8]	total loss	total loss

Path to Target: Tunnel Roadway

Scenario No.	Hazard or Threat	Tactical Delivery Device	Target	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
27H	Small IED	Backpack	Exposed Ductbank	**PV**	public access into roadway				
				OV	inadequate surveillance				
				DP	N/A	N/A	partial loss[7,8]	partial loss[7]	partial loss[7]
28H	Large Fire[1]	Tanker	Portal[4]	**PV**	uncontrolled vehicle access				
				OV	no cargo restrictions				
				DP	loss[6]	loss	loss[8]	loss	loss
29H	Large Fire[1]	Tanker	Any Tunnel Location Adjacent to Critical Facility[5]	**PV**	uncontrolled vehicle access				
				OV	no cargo restrictions				
				DP	partial loss[6]	partial loss	partial loss[8]	partial loss	partial loss
30H	HazMat	Truck	Any Tunnel Location	**PV**	uncontrolled vehicle access				
				OV	no cargo restrictions				
				DP	function loss[9]	function loss[9]	function loss[9]	function loss[9]	function loss[9]
31H	C/B/R	Vial/ Aerosol/ Package in Vehicle	Tunnel Occupants	**PV**	uncontrolled vehicle access				
				OV	no vehicle inspections at portals				
				DP	function loss[9]	N/A	N/A	N/A	N/A

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution

C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/ Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

Table 25. (Continued).

Path to Target: Tunnel Air Supply System
Target: Tunnel Occupants and Surrounding Population in Discharge Plume Area

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
32H	C/B/R	Vial/ Aerosol/ Package on Foot	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	functions as weapon delivery device[9]	N/A	N/A	N/A	N/A
33H	C/B/R	Vial/ Aerosol/ Package in Motor Vehicle	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	functions as weapon delivery device[9]	N/A	N/A	N/A	N/A

Path to Target: Virtual
Target: C&C Center

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
34H	Cyber Attack	Digital Virus Code	**PV**	insufficient or outdated electronic protection software				
			OV	insufficient or outdated electronic protection software				
			DP	N/A	N/A	N/A	total loss of or inappropriate traffic and MEC equipment control	N/A

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

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Table 26. Vulnerabilities to most likely hazard or threat scenarios for transit tunnels.

Path to Target: Surface Access Roadway
Target: Standalone Command and Control (C&C) Center

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
14T	Large IED	Truck	PV	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	N/A	N/A	N/A	total loss	total loss
15T	Medium IED	Car/Van	PV	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	N/A	total loss	total loss
16T	Small IED	Backpack[2]	PV	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	N/A	total loss	total loss

Path to Target: Surface Access Roadway
Target: Stand-Alone Substation

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
17T	Large IED	Truck	PV	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	N/A	N/A	total loss[8]	N/A	N/A
18T	Medium IED	Car/Van	PV	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	partial loss[8]	N/A	N/A
19T	Small IED	Backpack[2]	PV	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	total loss[8]	N/A	N/A

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

Table 26. (Continued).

Path to Target: Surface Access Roadway
Target: Ventilation Structure[3]

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
20T	Large IED	Truck	PV	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	total loss	total loss	total loss[8]	total loss	total loss
21T	Medium IED	Car/Van	PV	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	partial loss	total loss	partial loss[8]	partial loss	partial loss
22T	Small IED	Backpack[2]	PV	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	partial loss	total loss	partial loss[8]	partial loss	partial loss

Path to Target: Surface Access Roadway
Target: Station

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
23T	Large IED	Truck	PV	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	total loss	total loss	total loss[8]	total loss	total loss
24T	Small IED	Backpack[2]	PV	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	partial loss[10]	partial loss[10]	partial loss[8,10]	partial loss[10]	partial loss[10]

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

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Table 26. (Continued).

Path to Target: Trackway

Scenario No.	Hazard or Threat	Tactical Delivery Device	Target	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
25T	Small IED	Backpack	Exposed Ductbank or MEC Equipment	**PV**	public access into trackway				
				OV	inadequate access surveillance				
				DP	N/A	partial loss[7]	partial loss[7, 8]	partial loss[7]	partial loss[7]
26T	Small IED	Backpack on Foot in Train	Station	**PV**	open access to station				
				OV	no personal inspections				
				DP	partial loss[10]	partial loss[10]	partial loss[10]	partial loss[10]	partial loss[10]
27T	Large Fire[1]	IED on Train	Any Tunnel Location Adjacent to Critical Facility[5]	**PV**	uncontrolled access to trains				
				OV	no cargo restrictions; no personal inspections				
				DP	partial loss[6]	partial loss	partial loss	partial loss	partial loss
28T	Large Fire[1]	IED on Train	Portal[4]	**PV**	uncontrolled access to trains				
				OV	no cargo restrictions; no personal inspections				
				DP	partial loss[6]	partial loss	partial loss	partial loss	partial loss
29T	HazMat	Device on Train	Any Tunnel Location	**PV**	uncontrolled access to trains				
				OV	no cargo restrictions; no personal inspections				
				DP	function loss[9]	function loss[9]	function loss[9]	function loss[9]	function loss[9]
30T	C/B/R	Vial/ Aerosol/ Package on Foot in Train	Tunnel/ Station Occupants	**PV**	uncontrolled access to trains				
				OV	no cargo restrictions; no personal inspections				
				DP	function loss[9]	function loss[9]	function loss[9]	function loss[9]	function loss[9]

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

Table 26. (Continued).

Path to Target: Tunnel Air Supply System
Target: Tunnel Occupants and Surrounding Population in Discharge Plume Area

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
31T	C/B/R	Vial/ Aerosol/ Package on Foot	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	functions as weapon delivery device[9]	N/A	N/A	N/A	N/A
32T	C/B/R	Vial/ Aerosol/ Package in Motor Vehicle	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	functions as weapon delivery device[9]	N/A	N/A	N/A	N/A

Path to Target: Virtual
Target: C&C Center

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
33T	Cyber Attack	Digital Virus Code	**PV**	insufficient or outdated electronic protection software				
			OV	insufficient or outdated electronic protection software				
			DP	N/A	N/A	N/A	total loss of or inappropriate traffic and MEC equipment control	N/A

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

Table 27. Vulnerabilities to most likely hazard or threat scenarios for rail tunnels.

Path to Target: Surface Access Roadway
Target: Stand-Alone Command and Control (C&C) Center

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
14R	Large IED	Truck	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	N/A	N/A	N/A	total loss	total loss
15R	Medium IED	Car/Van	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	N/A	total loss	total loss
16R	Small IED	Backpack[2]	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	N/A	total loss	total loss

Path to Target: Surface Access Roadway
Target: Stand-Alone Substation

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
17R	Large IED	Truck	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	N/A	N/A	total loss[8]	N/A	N/A
18R	Medium IED	Car/Van	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	partial loss[8]	N/A	N/A
19R	Small IED	Backpack[2]	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	N/A	N/A	total loss[8]	N/A	N/A

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

Table 27. (Continued).

Path to Target: Surface Access Roadway
Target: Ventilation Structure[3]

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
20R	Large IED	Truck	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	total loss	total loss	total loss[8]	total loss	total loss
21R	Medium IED	Car/Van	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	partial loss	total loss	partial loss[8]	partial loss	partial loss
22R	Small IED	Backpack[2]	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	partial loss	total loss	partial loss[8]	partial loss	partial loss

Path to Target: Surface Access Roadway
Target: Station

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
23R	Large IED	Truck	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	total loss	total loss	total loss[8]	total loss	total loss
24R	Small IED	Backpack	**PV**	insufficient perimeter protection				
			OV	insufficient surveillance				
			DP	partial loss[10]	partial loss[10]	partial loss[8, 10]	partial loss[10]	partial loss[10]

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

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Table 27. (Continued).

Path to Target: Trackway

Scenario No.	Hazard or Threat	Tactical Delivery Device	Target	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
25R	Small IED	Backpack	Exposed Ductbank or MEC Equipment	**PV**	public access into trackway				
				OV	inadequate access surveillance				
				DP	N/A	partial loss[7]	partial loss[7, 8]	partial loss[7]	partial loss[7]
26R	Small IED	Backpack on Foot in Train	Station	**PV**	open access to station				
				OV	no personal inspections				
				DP	partial loss[10]	partial loss[10]	partial loss[10]	partial loss[10]	partial loss[10]
27R	Large Fire[1]	IED on Train	Any Tunnel Location Adjacent to Critical Facility[5]	**PV**	uncontrolled access to trains				
				OV	no cargo restrictions; no personal inspections				
				DP	partial loss[6]	partial loss	partial loss	partial loss	partial loss
28R	Large Fire[1]	IED on Train	Portal[4]	**PV**	uncontrolled access to trains				
				OV	no cargo restrictions; no personal inspections				
				DP	partial loss[6]	partial loss	partial loss	partial loss	partial loss
29R	HazMat	Device on Train	Any Tunnel Location	**PV**	uncontrolled access to trains				
				OV	no cargo restrictions; no personal inspections				
				DP	function loss[9]	function loss[9]	function loss[9]	function loss[9]	function loss[9]
30R	C/B/R	Vial/ Aerosol/ Package on Foot in Train	Tunnel/ Station Occupants	**PV**	uncontrolled access to trains				
				OV	no cargo restrictions; no personal inspections				
				DP	function loss[9]	function loss[9]	function loss[9]	function loss[9]	function loss[9]

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

Table 27. (Continued).

Path to Target: Tunnel Air Supply System
Target: Tunnel Occupants and Surrounding Population in Discharge Plume Area

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
31R	C/B/R	Vial/ Aerosol/ Package on Foot	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	functions as weapon delivery device[9]	N/A	N/A	N/A	N/A
32R	C/B/R	Vial/ Aerosol/ Package in Motor Vehicle	**PV**	insufficient perimeter protection				
			OV	insufficient access surveillance				
			DP	functions as weapon delivery device[9]	N/A	N/A	N/A	N/A

Path to Target: Virtual
Target: C&C Center

Scenario No.	Hazard or Threat	Tactical Delivery Device	PV/OV/DP	Vent. System	Life Safety Systems	Power Dist.	C&C	Comms.
33R	Cyber Attack	Digital Virus Code	**PV**	insufficient or outdated electronic protection software				
			OV	insufficient or outdated electronic protection software				
			DP	N/A	N/A	N/A	inappropriate or total loss of traffic and MEC equipment control	N/A

Abbreviations:
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential
Vent. = Ventilation
Dist. = Distribution
C&C = Command and Control
Comms. = Communications
HazMat = Hazardous Material
C/B/R = Chemical/Biological/Radiological
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators, or C&C centers
6. Partial loss of emergency ventilation due to high temperatures
7. Potential loss of downstream MEC systems or power to them
8. Unless you have dual power supply from both ends of the tunnel
9. Would require decontamination
10. Blast wave could propagate through station and destroy MEC equipment

CHAPTER 5

Countermeasures

5.1 Introduction

The main objective of this chapter is to identify and describe potential methods that can be used by tunnel owners and operators to make structural improvements (interior and exterior) and system improvements at critical locations for the purpose of improving the structural and operational security and safety of transportation tunnels and associated underground infrastructure (including stations, ventilation shafts, and electrical substations).

5.2 Hazard and Threat Directories

Hazard and threat directories are tables that compile the hazard and threat scenarios for a particular tunnel mode (i.e., road, transit, or rail) and direct the user to the appropriate countermeasure guides (Tables 34 through 41), which contain more detailed information.

5.2.1 Structural Hazard and Threat Directories

From the information contained in Section 4.4.2 (modes of tunnel failure) and Section 4.4.3 (effects of other extreme events), it was determined that explosives and large fires are the hazards and threats that must be considered when assessing structural vulnerability and damage potential. This finding, combined with other information contained in those sections, led to development of Table 28, which presents 13 hazard and threat scenarios within road tunnels that are considered to be the most critical from a structural standpoint. Similarly, Tables 29 and 30 were developed to present 13 hazard and threat scenarios that are considered to be the most critical for transit and rail tunnels, respectively.

In using Tables 28 through 30, the following steps should be performed:

1. Identify your tunnel by mode (road, transit, or rail) and choose the appropriate directory.
2. Identify your tunnel by "structural tunnel type" (immersed tube, cut-and-cover, bored or mined, air-rights structure), and eliminate the columns that don't apply to your facility.
3. Review each of the "hazard or threat scenario" columns to identify and eliminate rows that don't apply to your facility. For example, within the "path to target" column you may eliminate the "waterway" rows if your tunnel is not underwater.
4. Make a list of countermeasure guides (i.e., Tables 34 through 41) that you need to review based on the remaining cells.

5.2.2 System Hazard and Threat Directories

System hazard and threat directories were developed using information contained in Section 4.5.4 (potentially critical locations); Table 24 (vulnerabilities of critical locations); and Tables 25, 26, and 27 (system vulnerabilities to most likely hazard and threat scenarios for road, transit, and rail tunnels, respectively). These directories, presented as Tables 31, 32, and 33, show the hazard and threat scenarios that are considered to be the most critical from a system standpoint for road, transit, and rail tunnels, respectively.

The directories lead the user to more detailed information contained within the countermeasure guides, which are presented as Tables 34 through 41. In using the system hazard and threat directories (Tables 31 through 33), the following steps should be performed:

1. Identify your tunnel by mode (road, transit, or rail), and choose the appropriate system hazard and threat directory.
2. Identify system types within your facility under "targeted system" (ventilation system, life safety system, power distribution, command and control, and communications) to eliminate the columns that don't apply to your facility.
3. Review each of the "hazard or threat scenario" columns to identify and eliminate rows that don't apply to your facility.

Table 28. Structural hazard and threat directory for road tunnels.

Hazard or Threat Scenario					Structural Tunnel Type				
No.	**Hazard or Threat**	**Path to Target**	**Tactical Delivery Device**	**Target**	**Immersed Tube**	**Cut-and-Cover**	**Bored or Mined in Soft to Firm Ground**	**Bored or Mined in Strong Rock**	**Air-Rights Structure**
1H	Large IED	Tunnel Roadway	Truck	Liner	Table 34	Table 34	Table 34	Table 34	N/A
2H	Medium IED	Tunnel Roadway	Car/Van	Liner	Table 34	Table 34	Table 34	Table 34	N/A
3H	Small IED	Tunnel Roadway	Backpack	Liner	Table 34	Table 34	Table 34	Table 34	N/A
4H	Large Fire[1]	Tunnel Roadway	Tanker	Liner	Table 34	Table 34	Table 34	Table 34	N/A
5H	Large IED	Tunnel Roadway	Truck	Column/ Wall/Roof Slab	N/A	N/A	N/A	N/A	Table 36
6H	Medium IED	Tunnel Roadway	Car/Van	Column/ Wall/Roof Slab	N/A	N/A	N/A	N/A	Table 36
7H	Small IED	Tunnel Roadway	Backpack	Column/ Wall/Roof Slab	N/A	N/A	N/A	N/A	Table 36
8H	Large Fire[1]	Tunnel Roadway	Tanker	Column/ Wall/Roof Slab	N/A	N/A	N/A	N/A	Table 36
9H	Large Fire[1]	Tunnel Roadway	Tanker	Portal	Table 34	Table 34	Table 34	Table 34	Table 34
10H	Very Large IED	Waterway	Ship or Depth Charge from Ship	Portal or Shaft Wall	Table 37	N/A	Table 37	Table 37	N/A
11H	Very Large IED	Waterway	Depth Charge from Ship	Top of Tunnel	Table 38	N/A	Table 38	N/A	N/A
12H	Large IED	Surface Roadway over Tunnel	Truck	Roof Slab	N/A	Table 35	N/A	N/A	Table 35
13H	Medium IED	Surface Roadway over Tunnel	Truck or Multiple Backpacks	Roof Slab	N/A	Table 35	N/A	N/A	Table 35

Abbreviation:
N/A = Not Applicable

Note:
1. More than 341 MBTU per hour (100 MW)

Table 29. Structural hazard and threat directory for transit tunnels.

Hazard or Threat Scenario					Structural Tunnel Type				
No.	**Hazard or Threat**	**Path to Target**	**Tactical Delivery Device**	**Target**	**Immersed Tube**	**Cut-and-Cover**	**Bored or Mined in Soft to Firm Ground**	**Bored or Mined in Strong Rock**	**Air-Rights Structure**
1T	Large IED	Trackway	Transit Car/ Engine	Liner	Table 34	Table 34	Table 34	Table 34	N/A
2T	Medium IED	Trackway	Transit Car/ Engine or Multiple Backpacks	Liner	Table 34	Table 34	Table 34	Table 34	N/A
3T	Small IED	Trackway/ Stations/Shops/ Portals	Backpack	Liner	Table 34	Table 34	Table 34	Table 34	N/A
4T	Large Fire[1]	Trackway	IED on Transit Vehicle	Liner	Table 34	Table 34	Table 34	Table 34	N/A
5T	Large IED	Trackway	Transit Car/Engine	Column/ Wall/Roof Slab	N/A	N/A	N/A	N/A	Table 36
6T	Medium IED	Trackway	Transit Car/ Engine or Multiple Backpacks	Column/ Wall/Roof Slab	N/A	N/A	N/A	N/A	Table 36
7T	Small IED	Trackway/ Stations/Shops/ Portals	Backpack	Column/ Wall/Roof Slab	N/A	N/A	N/A	N/A	Table 36
8T	Large Fire[1]	Trackway	IED on Transit Vehicle	Column/ Wall/Roof Slab	N/A	N/A	N/A	N/A	Table 36
9T	Large Fire[1]	Trackway	IED on Transit Vehicle	Portal	Table 34	Table 34	Table 34	Table 34	Table 34
10T	Very Large IED	Waterway	Ship or Depth Charge from Ship	Portal or Shaft Wall	Table 37	N/A	Table 37	Table 37	N/A
11T	Very Large IED	Waterway	Depth Charge from Ship	Top of Tunnel	Table 38	N/A	Table 38	N/A	N/A
12T	Large IED	Surface Roadway over Tunnel	Truck	Roof Slab	N/A	Table 35	N/A	N/A	Table 35
13T	Medium IED	Surface Roadway over Tunnel	Truck or Multiple Backpacks	Roof Slab	N/A	Table 35	N/A	N/A	Table 35

Abbreviation:
N/A = Not Applicable

Note:
1. More than 341 MBTU per hour (100 MW)

Table 30. Structural hazard and threat directory for rail tunnels.

Hazard or Threat Scenario					Structural Tunnel Type				
No.	Hazard or Threat	Path to Target	Tactical Delivery Device	Target	Immersed Tube	Cut-and-Cover	Bored or Mined in Soft to Firm Ground	Bored or Mined in Strong Rock	Air-Rights Structure
1R	Large IED	Trackway	Rail Car/Engine	Liner	Table 34	Table 34	Table 34	Table 34	N/A
2R	Medium IED	Trackway	Rail Car/Engine or Multiple Backpacks	Liner	Table 34	Table 34	Table 34	Table 34	N/A
3R	Small IED	Trackway/ Stations/Shops/ Portals	Backpack	Liner	Table 34	Table 34	Table 34	Table 34	N/A
4R	Large Fire[1]	Trackway	IED on Rail Vehicle	Liner	Table 34	Table 34	Table 34	Table 34	N/A
5R	Large IED	Trackway	Rail Car/Engine	Column/Wall/ Roof Slab	N/A	N/A	N/A	N/A	Table 36
6R	Medium IED	Trackway	Rail Car/Engine or Multiple Backpacks	Column/Wall/ Roof Slab	N/A	N/A	N/A	N/A	Table 36
7R	Small IED	Trackway/ Stations/Shops/ Portals	Backpack	Column/Wall/ Roof Slab	N/A	N/A	N/A	N/A	Table 36
8R	Large Fire[1]	Trackway	IED on Rail Vehicle	Column/Wall/ Roof Slab	N/A	N/A	N/A	N/A	Table 36
9R	Large Fire[1]	Trackway	IED on Rail Vehicle	Portal	Table 34	Table 34	Table 34	Table 34	Table 34
10R	Very Large IED	Waterway	Ship or Depth Charge from Ship	Portal or Shaft Wall	Table 37	N/A	Table 37	Table 37	N/A
11R	Very Large IED	Waterway	Depth Charge from Ship	Top of Tunnel	Table 38	N/A	Table 38	N/A	N/A
12R	Large IED	Surface Roadway over Tunnel	Truck	Roof Slab	N/A	Table 35	N/A	N/A	Table 35
13R	Medium IED	Surface Roadway over Tunnel	Truck or Multiple Backpacks	Roof Slab	N/A	Table 35	N/A	N/A	Table 35

Abbreviation:
N/A = Not Applicable

Note:
1. More than 341 MBTU per hour (100 MW)

Table 31. System hazard and threat directory for road tunnels.

Hazard or Threat Scenario					Targeted System				
No.	Hazard or Threat	Path to Target	Tactical Delivery Device	Target	Ventilation System	Life Safety System	Power Distribution	Command and Control	Comms.
14H	Large IED	Surface Roadway	Truck	C&C Center	N/A	N/A	N/A	Table 39	Table 39
15H	Medium IED	Surface Roadway	Car/Van	C&C Center	N/A	N/A	N/A	Table 39	Table 39
16H	Small IED	Surface Roadway	Backpack[2]	C&C Center	N/A	N/A	N/A	Table 39	Table 39
17H	Large IED	Surface Roadway	Truck	Substation	N/A	N/A	Table 39	N/A	N/A
18H	Medium IED	Surface Roadway	Car/Van	Substation	N/A	N/A	Table 39	N/A	N/A
19H	Small IED	Surface Roadway	Backpack[2]	Substation	N/A	N/A	Table 39	N/A	N/A
20H	Large IED	Surface Roadway	Truck	Vent. Structure[3]	Table 39	Table 39	Table 39	Table 39	Table 39
21H	Medium IED	Surface Roadway	Car/Van	Vent. Structure[3]	Table 39	Table 39	Table 39	Table 39	Table 39
22H	Small IED	Surface Roadway	Backpack[2]	Vent. Structure[3]	Table 39	Table 39	Table 39	Table 39	Table 39
23H	Large IED	Tunnel Roadway	Truck	C&C Center Above or Adjacent to the Tunnel	N/A	N/A	N/A	Table 34	Table 34
24H	Medium IED	Tunnel Roadway	Car/Van	C&C Center Above or Adjacent to the Tunnel	N/A	N/A	N/A	Table 34	Table 34
25H	Large IED	Tunnel Roadway	Truck	Vent. Structure Above or Adjacent to the Tunnel	Table 34	Table 34	Table 34	Table 34	Table 34
26H	Medium IED	Tunnel Roadway	Car/Van	Vent. Structure Above or Adjacent to the Tunnel	Table 34	Table 34	Table 34	Table 34	Table 34

Table 31. (Continued).

Hazard or Threat Scenario					Targeted System				
No.	**Hazard or Threat**	**Path to Target**	**Tactical Delivery Device**	**Target**	**Ventilation System**	**Life Safety System**	**Power Distribution**	**Command and Control**	**Comms.**
27H	Small IED	Tunnel Roadway	Backpack	Exposed Ductbank	N/A	N/A	Table 34	Table 34	Table 34
28H	Large Fire[1]	Tunnel Roadway	Tanker	Portal[4]	Table 34	Table 34	Table 34	Table 34	Table 34
29H	Large Fire[1]	Tunnel Roadway	Tanker	Any Tunnel Location Adjacent to Critical Facility[5]	Table 34	Table 34	Table 34	Table 34	Table 34
30H	HazMat	Tunnel Roadway	Truck	Any Tunnel Location	Table 34	Table 34	Table 34	Table 34	Table 34
31H	C/B/R	Tunnel Roadway	Vial/Aerosol/ Package	Tunnel Occupants	Table 34	Table 34	Table 34	Table 34	Table 34
32H	C/B/R	Tunnel Supply Air System	Vial/Aerosol/ Package	Tunnel and Discharge Plume Area Occupants	Table 40	N/A	N/A	N/A	N/A
33H	C/B/R	Tunnel Supply Air System	Vial/Aerosol/ Package	Tunnel and Discharge Plume Area Occupants	Table 40	N/A	N/A	N/A	N/A
34H	Cyber Attack	Virtual	Digital Virus Code	C&C Center	N/A	N/A	N/A	Table 41	N/A

Abbreviations:
Vent. = Ventilation
Comms. = Communications
C&C = Command and Control
C/B/R = Chemical/Biological/Radiological
HazMat = Hazardous Material
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans is housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators or C&C centers

Table 32. System hazard and threat directory for transit tunnels.

Hazard or Threat Scenario					Targeted System				
No.	**Hazard or Threat**	**Path to Target**	**Tactical Delivery Device**	**Target**	**Ventilation System**	**Life Safety System**	**Power Distribution**	**Command and Control**	**Comms.**
14T	Large IED	Surface Roadway	Truck	C&C Center	N/A	N/A	N/A	Table 39	Table 39
15T	Medium IED	Surface Roadway	Car/Van	C&C Center	N/A	N/A	N/A	Table 39	Table 39
16T	Small IED	Surface Roadway	Backpack[2]	C&C Center	N/A	N/A	N/A	Table 39	Table 39
17T	Large IED	Surface Roadway	Truck	Substation	N/A	N/A	Table 39	N/A	N/A
18T	Medium IED	Surface Roadway	Car/Van	Substation	N/A	N/A	Table 39	N/A	N/A
19T	Small IED	Surface Roadway	Backpack[2]	Substation	N/A	N/A	Table 39	N/A	N/A
20T	Large IED	Surface Roadway	Truck	Vent. Structure[3]	Table 39	Table 39	Table 39	Table 39	Table 39
21T	Medium IED	Surface Roadway	Car/Van	Vent. Structure[3]	Table 39	Table 39	Table 39	Table 39	Table 39
22T	Small IED	Surface Roadway	Backpack	Vent. Structure[3]	Table 39	Table 39	Table 39	Table 39	Table 39
23T	Large IED	Surface Roadway	Truck	Station	Table 39	Table 39	Table 39	Table 39	Table 39
24T	Small IED	Surface Roadway	Backpack[2]	Station	Table 39	Table 39	Table 39	Table 39	Table 39
25T	Small IED	Trackway	Backpack	Exposed Ductbank or MEC Equipment	N/A	Table 34	Table 34	Table 34	Table 34
26T	Small IED	Trackway	Backpack[2]	Station	Table 34	Table 34	Table 34	Table 34	Table 34

Table 32. (Continued).

Hazard or Threat Scenario					Targeted System				
No.	**Hazard or Threat**	**Path to Target**	**Tactical Delivery Device**	**Target**	**Ventilation System**	**Life Safety System**	**Power Distribution**	**Command and Control**	**Comms.**
27T	Large Fire[1]	Trackway	Incendiary Device on Train	Portal[2]	Table 34	Table 34	Table 34	Table 34	Table 34
28T	Large Fire[1]	Trackway	Incendiary Device on Train	Any Tunnel Location Adjacent to Critical Facility[5]	Table 34	Table 34	Table 34	Table 34	Table 34
29T	Hazardous Materials	Trackway	Device on Train	Any Tunnel Location	Table 34	Table 34	Table 34	Table 34	Table 34
30T	C/B/R	Trackway	Vial/Aerosol/ Package on Train	Tunnel/Station Occupants	Table 34	Table 34	Table 34	Table 34	Table 34
31T	C/B/R	Tunnel Air Supply System	Vial/Aerosol/ Package	Tunnel/Station and Discharge Plume Area Occupants	Table 40	N/A	N/A	N/A	N/A
32T	C/B/R	Tunnel Air Supply System	Vial/Aerosol/ Package	Tunnel/Station and Discharge Plume Area Occupants	Table 40	N/A	N/A	N/A	N/A
33T	Cyber Attack	Virtual	Digital Virus Code	C&C Center	N/A	N/A	N/A	Table 41	N/A

Abbreviations:
Vent. = Ventilation
Comms. = Communications
C&C = Command and Control
C/B/R = Chemical/Biological/Radiological
HazMat = Hazardous Material
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans is housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators or C&C centers

Table 33. System hazard and threat directory for rail tunnels.

Hazard or Threat Scenario					Targeted System				
No.	Hazard or Threat	Path to Target	Tactical Delivery Device	Target	Ventilation System	Life Safety System	Power Distribution	Command and Control	Comms.
14R	Large IED	Surface Roadway	Truck	C&C Center	N/A	N/A	N/A	Table 39	Table 39
15R	Medium IED	Surface Roadway	Car/Van	C&C Center	N/A	N/A	N/A	Table 39	Table 39
16R	Small IED	Surface Roadway	Backpack[2]	C&C Center	N/A	N/A	N/A	Table 39	Table 39
17R	Large IED	Surface Roadway	Truck	Substation	N/A	N/A	Table 39	N/A	N/A
18R	Medium IED	Surface Roadway	Car/Van	Substation	N/A	N/A	Table 39	N/A	N/A
19R	Small IED	Surface Roadway	Backpack[2]	Substation	N/A	N/A	Table 39	N/A	N/A
20R	Large IED	Surface Roadway	Truck	Ventilation Structure[3]	Table 39	Table 39	Table 39	Table 39	Table 39
21R	Medium IED	Surface Roadway	Car/Van	Ventilation Structure [3]	Table 39	Table 39	Table 39	Table 39	Table 39
22R	Small IED	Surface Roadway	Backpack[2]	Ventilation Structure[3]	Table 39	Table 39	Table 39	Table 39	Table 39
23R	Large IED	Surface Roadway	Truck	Station	Table 39	Table 39	Table 39	Table 39	Table 39
24R	Small IED	Surface Roadway	Backpack[2]	Station	Table 39	Table 39	Table 39	Table 39	Table 39
25R	Small IED	Trackway	Backpack	Exposed Ductbank or MEC equipment	N/A	Table 34	Table 34	Table 34	Table 34
26R	Small IED	Trackway	Backpack[2]	Station	Table 34	Table 34	Table 34	Table 34	Table 34

Table 33. (Continued).

Hazard or Threat Scenario					Targeted System				
No.	Hazard or Threat	Path to Target	Tactical Delivery Device	Target	Ventilation System	Life Safety System	Power Distribution	Command and Control	Comms.
27R	Large Fire[1]	Trackway	Incendiary Device on Train	Portal[4]	Table 34	Table 34	Table 34	Table 34	Table 34
28R	Large Fire[1]	Trackway	Incendiary Device on Train	Any Tunnel Location Adjacent to Critical Facility[5]	Table 34	Table 34	Table 34	Table 34	Table 34
29R	Hazardous Materials	Trackway	Device on Train	Any Tunnel Location	Table 34	Table 34	Table 34	Table 34	Table 34
30R	C/B/R	Trackway	Vial/Aerosol/ Package on Train	Tunnel/Station Occupants	Table 34	Table 34	Table 34	Table 34	Table 34
31R	C/B/R	Tunnel Air Supply System	Vial/Aerosol/ Package	Tunnel/Station and Discharge Plume Area Occupants	Table 40	N/A	N/A	N/A	N/A
32R	C/B/R	Tunnel Air Supply System	Vial/ Aerosol/ Package	Tunnel/Station and Discharge Plume Area Occupants	Table 40	N/A	N/A	N/A	N/A
33R	Cyber Attack	Virtual	Digital Virus Code	C&C Center	N/A	N/A	N/A	Table 41	N/A

Abbreviations:
Vent. = Ventilation
Comms. = Communications
C&C = Command and Control
C/B/R = Chemical/Biological/Radiological
HazMat = Hazardous Material
N/A = Not Applicable

Notes:
1. More than 341 MBTU per hour (100 MW)
2. Assumes perpetrator gets inside
3. Assumes transverse system or longitudinal with fans is housed in central location
4. Worst case is downhill, unidirectional tunnel
5. Such as ventilation buildings, substations, emergency generators or C&C centers

Table 34. Countermeasure guide.

Hazard or Threat Scenario Nos.: 1H-4H, 9H, 23H-31H; 1T-4T, 9T, 25T-30T; 1R-4R, 9R, 25R-30R

PV: insufficient tunnel liner thickness; inadequate tunnel cover; relative proximity of hazard or threat to liner

OV: uncontrolled access of vehicles into tunnels; insufficient vehicle inspections and/or cargo restrictions

DP: tunnel collapse requiring up to several months to repair; rapid flooding and inflow of granular backfill material for underwater tunnels; total or partial loss of system function

CM Type	CM Functions and Descriptions	Relative Effectiveness	Order-of-Magnitude Cost	P/Op	Strategy	Multiple-Benefit Potential	CM #
Minimum Measures	Lighting	H	M	P	DR	Anti-Theft, Safety	1
	Ventilation System	H	VH	P, Op	M	Safety	2
	Fire Detection System	M	L	P	DT	Safety	3
	Fire Protection System	H	H	P, Op	M	Safety	4
	CCTV System or CCVE	H	M	P, Op	DT, I	Traffic Surveillance	5
	Security Awareness Training	H	L	Op	DT, M		6
	Roving Patrols	M	L	Op	DR, DT, I	Safety, Security	7
	HazMat Restrictions	L	L	Op	DR	Safety, Security	8
	Background Checks	L	L	Op	DR, DT	Identify Unqualified Employees	9
	Full-Scale Emergency Response Exercises	H	L	Op	DT, I, M		19
Measures for an Elevated Threat Level	Guards at Portals	H	L	Op	DR, DT, I	Public Assurance	20
	Inspections (Personal/Vehicle)	H	L	Op	DR, DT, I	Public Assurance	21
	Bomb-Sniffing Dogs	M	L	Op	DR, DT	Public Assurance	22
	Onsite Credential Checks	L	L	Op	DR	Anti-Theft	23
	Explosive Detectors—Mobile	H	L	P	DT		26
Permanent Enhancements	Explosive Detectors—Fixed	H	M	P	DT		28
	Interior Liner Steel Plates or Panels[1,2,3]	H	VH[6]	P	M	Decrease Maintenance, Increase Usable Life of Structure	31
	Interior Liner Concrete Panels[1,2]	H	VH[6]	P	M		32
	Interior Concrete or Chemical Grouting	M[4]	VH[6]	P	M		33
	Interior Liner Bolting or Tie-Backs[1,2]	M[4]	H[6]	P	M		34
	Exterior (Ground) Concrete or Chemical Grouting	H[4]	VH	P	M		35
	Rip-Rap over Tunnel[5]	H	VH	P	M	Erosion Protection	36
	Precast Concrete Slab over Tunnel[5]	H	VH	P	M	Erosion Protection	37
	Disperse Functions (i.e., Redundant Systems)	H	H	P	M	Decrease Maintenance, Increase Usable Life of Systems	

Footnotes

1. If operating environment and/or clearances allow.
2. Thickness of steel plates or panels, concrete panels, and shotcrete depends on size of IED or fire.
3. For very large fires, steel liner must be one continuous, seamless plate and attaching mechanisms must be fire-resistant.
4. Effectiveness will depend on surrounding soil properties.
5. Underwater tunnel only—amount of rip-rap and thickness of concrete slab depends on size of IED.
6. Cost may increase due to low-clearance applications, electrified transit and rail tunnels, track outage durations, bonding, and grounding.

Table 35. Countermeasure guide.

Hazard or Threat Scenario Nos.: 12H, 13H; 12T, 13T; 12R, 13R

PV: insufficient roof slab thickness; inadequate tunnel cover; relative proximity of hazard or threat to roof slab

OV: uncontrolled access of vehicles into tunnels; insufficient vehicle inspections and/or cargo restrictions

DP: tunnel collapse requiring up to several months to repair; total or partial loss of system function

CM Type	CM Functions and Descriptions	Relative Effectiveness	Order-of-Magnitude Cost	P/Op	Strategy	Multiple-Benefit Potential	CM #
Minimum Measures	Lighting	H	M	P	DR	Anti-Theft, Safety	1
	Ventilation System	H	VH	P, Op	M	Safety	2
	Fire Detection System	M	L	P	DT	Safety	3
	Fire Protection System	H	H	P, Op	M	Safety	4
	CCTV System or CCVE	H	M	P, Op	DT, I	Traffic Surveillance	5
	Security Awareness Training	H	L	Op	DT, M		6
	Roving Patrols	M	L	Op	DR, DT, I	Safety, Security	7
	HazMat Restrictions	L	L	Op	DR	Safety, Security	8
	Background Checks	L	L	Op	DR, DT	Identify Unqualified Employees	9
	Full-Scale Emergency Response Exercises	H	L	Op	DT, I, M		19
Measures for an Elevated Threat Level	Guards at Portals	H	L	Op	DR, DT, I	Public Assurance	20
	Inspections (Personal/Vehicle)	H	L	Op	DR, DT, I	Public Assurance	21
	Bomb-Sniffing Dogs	M	L	Op	DR, DT	Public Assurance	22
	Onsite Credential Checks	L	L	Op	DR	Anti-Theft	23
	Explosive Detectors—Mobile	H	L	P	DT		26
Permanent Enhancements	Explosive Detectors—Fixed	H	M	P	DT		28
	Interior Roof Steel Plates[1,2]	H	VH	P	M	Decrease Maintenance, Increase Usable Life of Structure	38
	Interior Roof Concrete Panels[1,2]	H	VH	P	M		39
	Exterior Roof Steel Plates[1,2]	H	VH	P	M		40
	Exterior Roof Concrete Panels[1,2]	H	VH	P	M		41
	Disperse Functions (i.e., Redundant Systems)	H	H	P	M	Decrease Maintenance, Increase Usable Life of Systems	

Footnotes
1. If operating environment and/or clearances allow.
2. Thickness of steel plates or panels, concrete panels, and shotcrete depends on size of IED or fire.
3. Effectiveness will depend on surrounding soil properties.
4. Underwater tunnel only—amount of rip-rap and thickness of concrete slab depends on size of IED.
5. Cost may increase due to low-clearance applications, electrified transit and rail tunnels, track outage durations, bonding, and grounding.

Table 36. Countermeasure guide.

Hazard or Threat Scenario Nos.: 5H-8H; 5T-8T; 5R-8R

PV: insufficient column/wall/roof slab protection within air-rights structure

OV: uncontrolled access of vehicles into tunnels; insufficient vehicle inspections and/or cargo restrictions

DP: extensive column/wall/roof slab damage requiring up to several months to repair; total or partial loss of system function

CM Type	CM Functions and Descriptions	Relative Effectiveness	Order-of-Magnitude Cost	P/Op	Strategy	Multiple-Benefit Potential	CM #
Minimum Measures	Lighting	H	M	P	DR	Anti-Theft, Safety	1
	Ventilation System	H	VH	P, Op	M	Safety	2
	Fire Detection System	M	L	P	DT	Safety	3
	Fire Protection System	H	H	P, Op	M	Safety	4
	CCTV System or CCVE	H	M	P, Op	DT, I	Traffic Surveillance	5
	Security Awareness Training	H	L	Op	DT, M		6
	Roving Patrols	M	L	Op	DR, DT, I	Safety, Security	7
	HazMat Restrictions	L	L	Op	DR	Safety, Security	8
	Background Checks	L	L	Op	DR, DT	Identify Unqualified Employees	9
	Full-Scale Emergency Response Exercises	H	L	Op	DT, I, M		19
Measures for an Elevated Threat Level	Guards at Portals	H	L	Op	DR, DT, I	Public Assurance	20
	Inspections (Personal/Vehicle)	H	L	Op	DR, DT, I	Public Assurance	21
	Bomb-Sniffing Dogs	M	L	Op	DR, DT	Public Assurance	22
	Onsite Credential Checks	L	L	Op	DR	Anti-Theft	23
	Explosive Detectors—Mobile	H	L	P	DT		26
Permanent Enhancements	Explosive Detectors—Fixed	H	M	P	DT		28
	Interior Roof Steel Plates[1,2]	H	VH	P	M		38
	Interior Roof Concrete[1,2] Panels	H	VH	P	M		39
	Bollards to Control Access	H	L	P	DR, DT	Pedestrian and User Safety, Anti-Trespassing	42
	Fencing to Control Access	H	L	P	DR, DT		43
	Concrete Encasement[1,2] of Columns	M	L	P	M	Decrease Maintenance, Increase Usable Life of Structure	44
	RFP Wrapping[1,2] of Columns	M	L	P	M		45
	Steel Jacketing[1,2] of Columns	M	L	P	M		46
	Redundant Columns or Walls[1,2]	H	H	P	M		47
	Disperse Functions (i.e., Redundant Systems)	H	H	P	M	Decrease Maintenance, Increase Usable Life of Systems	

Footnotes
1. If operating environment and/or clearances allow.
2. Thickness of steel plates or panels, concrete panels, and shotcrete depends on size of IED or fire.
3. Effectiveness will depend on surrounding soil properties.
4. Underwater tunnel only—amount of rip-rap and thickness of concrete slab depends on size of IED.
5. Cost may increase due to low-clearance applications, electrified transit and rail tunnels, track outage durations, bonding, and grounding.

Table 37. Countermeasure guide.

Hazard or Threat Scenario Nos.: 10H; 10T; 10R

PV: insufficient portal/shaft wall strength

OV: uncontrolled water traffic; insufficient ship inspections and surveillance

DP: tunnel collapse causing operational disruption and requiring up to several weeks to repair; rapid flooding if portal/shaft wall is close to the water

CV Type	CM Functions and Descriptions	Relative Effectiveness	Order-of-Magnitude Cost	P/Op	Strategy	Multiple-Benefit Potential	CM #
Minimum Measures	Background Checks	L	L	Op	DR, DT	Identify Unqualified Employees	9
	Full-Scale Emergency Response Exercises	H	L	Op	DT, I, M		19
Measures for an Elevated Threat Level	Inspections (Personal/Vehicle)	H	L	Op	DR, DT, I	Safety	21
	Bomb-Sniffing Dogs	M	L	Op	DR, DT, I	Public Assurance	22
	Onsite Credential Checks	L	L	Op	DR, DT	Anti-Trespassing	23
	Waterborne Patrols	M	L	Op	DR, DT, I	Safety	24
	Ship-Tracking Protocols	M	L	Op	DT	Dock Scheduling	25
Permanent Enhancements	Interior Liner Steel Plates or Panels[1,2,4]	H	VH[6]	P	M	Decrease Maintenance, Increase Usable Life of Structure	31
	Interior Liner Concrete Panels[1,2]	H	VH[6]	P	M		32
	Interior Concrete or Chemical Grouting	M[5]	VH[6]	P	M		33
	Interior Liner Bolting or Tie-Backs[1,2]	M[5]	H[6]	P	M		34
	Exterior (Ground) Concrete or Chemical Grouting	H[5]	VH	P	M	Decrease Maintenance, Increase Usable Life of Structure	35
	Floodgates[1,7]	M	VH[6]	P	M		48
	Barrier Walls[3]	H	H	P	DR, M	Increase Usable Life of Structure	49
	Bollards[3] or Fenders in the Water	H	H	P	DR, M	Increase Usable Life of Structure	50

Footnotes
1. If operating environment and/or clearances allow.
2. Thickness of steel plates or panels, concrete panels, and shotcrete depends on size of IED or fire.
3. Thickness of barrier walls, bollards, or fender system depends on size of IED and distance of portal/shaft wall to water traffic.
4. For very large fires, steel liner must be one continuous, seamless plate and the attaching mechanisms must be fire-resistant.
5. Effectiveness will depend on surrounding soil properties.
6. Cost may increase due to low-clearance applications, electrified transit and rail tunnels, track outage durations, bonding, and grounding.
7. Effectiveness will depend on physical dimensions of the tunnel.

Table 38. Countermeasure guide.

Hazard or Threat Scenario Nos.: 11H; 11T; 11R

PV: insufficient strength of tunnel top

OV: uncontrolled water traffic; insufficient ship inspections and surveillance

DP: tunnel collapse causing operational disruption and requiring up to several weeks to repair; rapid flooding if portal/shaft wall is close to the water

CM Type	CM Functions and Descriptions	Relative Effectiveness	Order-of-Magnitude Cost	P/Op	Strategy	Multiple-Benefit Potential	CM #
Minimum Measures	Background Checks	L	L	Op	DR, DT	Identify Unqualified Employees	9
	Full-Scale Emergency Response Exercises	H	L	Op	DT, I, M		19
Measures for an Elevated Threat Level	Inspections (Personal/Vehicle)	H	L	Op	DR, DT, I	Safety	21
	Bomb-Sniffing Dogs	M	L	Op	DR, DT, I	Public Assurance	22
	Onsite Credential Checks	L	L	Op	DR, DT	Anti-Trespassing	23
	Waterborne Patrols	M	L	Op	DR, DT, I	Safety	24
	Ship-Tracking Protocols	M	L	Op	DT	Dock Scheduling	25
Permanent Enhancements	Interior Liner Steel Plates or Panels[1,2,3]	H	VH[5]	P	M	Decrease Maintenance, Increase Usable Life of Structure	31
	Interior Liner Concrete Panels[1,2]	H	VH[5]	P	M		32
	Interior Concrete or Chemical Grouting	M[4]	VH[5]	P	M		33
	Interior Liner Bolting or Tie-Backs[1,2]	M[4]	H[5]	P	M		34
	Rip-Rap over Tunnel[7]	H	H	P	M	Erosion Protection	36
	Precast Concrete Slab over Tunnel[7]	H	H	P	M	Erosion Protection	37
	Floodgates[1,6]	M	VH[5]	P	M		48

Footnotes
1. If operating environment and/or clearances allow.
2. Thickness of steel plates or panels, concrete panels, and shotcrete depends on size of IED or fire.
3. For very large fires, steel liner must be one continuous, seamless plate and the attaching mechanisms must be fire-resistant.
4. Effectiveness will depend on surrounding soil properties.
5. Cost may increase due to low-clearance applications, electrified transit and rail tunnels, track outage durations, bonding, and grounding.
6. Effectiveness will depend on physical dimensions of the tunnel.
7. Amount of rip-rap and thickness of concrete slab depend on size of IED.

Table 39. Countermeasure guide.

Hazard or Threat Scenario Nos.: 14H-22H; 14T-24T; 14R-24R

PV: insufficient perimeter protection of critical structure

OV: insufficient surveillance of critical structure

DP: total or partial loss of system function

CM Type	CM Functions and Descriptions	Relative Effectiveness	Order-of-Magnitude Cost	P/Op	Strategy	Multiple-Benefit Potential	CM #
Minimum Measures	Lighting	H	L	P	DR	Anti-Theft, Safety	1
	Ventilation System	H	M	P, Op	M	Safety	2
	Fire Detection System	M	L	P	DT	Safety	3
	Fire Protection System	H	H	P, Op	M	Safety	4
	CCTV System or CCVE	H	M	P, Op	DT, I	Traffic Surveillance	5
	Security Awareness Training	H	L	Op	DT, M		6
	Roving Patrols	M	L	Op	DR, DT, I	Safety, Security	7
	HazMat Restrictions	L	L	Op	DR	Safety, Security	8
	Access Controls (Bollards, Fences, Walls, Locks)	H	L	P	DR, DT	Pedestrian and User Safety, Anti-Trespassing	10
	Employee Identification System	H	L	P	DR	Work Hour Tracking	11
	Intrusion Detection System	H	M	P	DT, I	Anti-Trespassing	12
	Evacuation Protocols	L	H	Op	M	Applicable to Any Hazard	13
	Full-Scale Emergency Response Exercises	H	L	Op	DT, I, M		19
Measures for an Elevated Threat Level	Inspections (Personal/Vehicle)	H	L	Op	DR, DT, I	Public Assurance	21
	Bomb-Sniffing Dogs	M	L	Op	DR, DT, I	Public Assurance	22
	Onsite Credential Checks	H	L	Op	DR, DT, I	Anti-Trespassing	23
	Explosive Detectors—Mobile	H	L	P	DT, I		26
Permanent Enhancements	Explosive Detectors—Fixed	H	M	P	DT, I		28
	Disperse Functions (i.e., Operate Redundant Systems)	H	H	P	M	Increase Usable Life of Systems	

Table 40. Countermeasure guide.

Hazard or Threat Scenario Nos.: 32H, 33H; 31T, 32T; 31R, 32R

PV: insufficient perimeter protection of ventilation intakes with respect to C/B/R

OV: insufficient surveillance of ventilation intakes with respect to C/B/R

DP: loss of life; required decontamination of vent system and facility

CM Type	CM Functions and Descriptions	Relative Effectiveness	Order-of-Magnitude Cost	P/Op	Strategy	Multiple-Benefit Potential	CM #
Minimum Measures	Lighting	H	L	P	DR, DT	Traffic Safety	1
	CCTV System or CCVE	H	M	P, Op	DT, I	Traffic Surveillance	5
	Security Awareness Training	M	L	Op	DT, I, M		6
	Roving Patrols	M	L	Op	DR, DT, I	Safety, Security	7
	Access Controls (Bollards, Fences, Walls, Locks)	M	M	P	DR	Safety	10
	Intrusion Detection System	H	M	P	DT	Anti-Trespassing	12
	Extend/Heighten Supply Air Intakes	H	M	P	DT		14
	Full-Scale Emergency Response Exercises	H	L	Op	DT, I, M		19
Measures for an Elevated Threat Level	Inspections (Personal/Vehicles)	H	L	Op	DT	Public Assurance	21
	C/B/R Detectors—Mobile	H	M	P	DT		27
Permanent Enhancements	Access Controls (Concrete Walls)	H	L[1]	P	DR	Safety	10
	C/B/R Detectors—Fixed	H	M	P	DT		29
	Redundant Ventilation Systems	H	VH	P	M	Increase Usable Life of Systems	30
	Integrate Ventilation System Operation with C/B/R Detectors	H	M	Op	M		

Footnote
1. Cost of wall depends on height and length.

Table 41. Countermeasure guide.

Hazard or Threat Scenario Nos.: 34H; 33T; 33R

PV: insufficient or outdated electronic protection software

OV: insufficient or outdated electronic protection software

DP: lost or inappropriate traffic and MEC equipment control

CM Type	CM Functions and Descriptions	Relative Effectiveness	Order-of-Magnitude Cost	P/Op	Strategy	Multiple-Benefit Potential	CM #
Minimum Measures	Background Checks	M	L	Op	DR, DT	Protect Integrity of Data and Signals, Protect Investment in Digital Systems	9
	Anti-Virus Software	H	L	P, Op	I		15
	Computer Firewalls	H	L	P, Op	I		16
	Backup Manual Control of Systems	H	M	P, Op	M		17
	Regularly Scheduled Data Backup	H	L	Op	M		18

For example, within the "hazard or threat" column you may eliminate the "HazMat" row if restrictions are already in place in your tunnel. You may also be able to eliminate whole columns (for example, you may eliminate the "substation" column if you don't have a substation).

4. Make a list of countermeasure guides (i.e., Tables 34 through 41) that you need to review based on the remaining cells.

5.3 Countermeasure Guides

5.3.1 Introduction

The countermeasure guides (Tables 34 through 41) contain a great deal of information in a compressed amount of space. Each of these guides describes various countermeasures that can be considered for a number of hazard or threat scenarios outlined in Tables 14 through 16 (structural vulnerabilities to most likely hazard and threat scenarios) and Tables 25 through 27 (system vulnerabilities to most likely hazard and threat scenarios). For example, Table 34 groups together scenarios 1H–4H and 9H from Table 28, 1T–4T and 9T from Table 29, and 1R–4R and 9R from Table 30. All of these scenarios have common physical vulnerabilities (i.e., insufficient tunnel liner thickness, inadequate tunnel cover, and relative proximity of hazard or threat to liner), operational vulnerabilities (i.e., uncontrolled access of vehicles into tunnels and insufficient vehicle inspections and/or cargo restrictions), and damage potentials (i.e., tunnel collapse requiring up to several months to repair, rapid flooding and inflow of granular backfill material for underwater tunnels, and total or partial loss of system function). Thus, the possible countermeasures for all of these scenarios are the same. For another example, Table 39 groups together scenarios 14H–22H from Table 31, 14T–24T from Table 32, and 14R–24R from Table 33. All of these scenarios have common physical vulnerabilities (i.e., insufficient perimeter protection of a critical facility), operational vulnerabilities (i.e., insufficient surveillance of a critical structure), and damage potentials (i.e., total or partial loss of system function). Thus, the possible countermeasures for all of these scenarios are the same.

5.3.2 Information Contained in Countermeasure Guides

Text Above the Table

The first line of text above the tables in each countermeasure guide identifies the applicable hazard or threat scenarios from the directories (Tables 28 through 33). This identification is a way to cross-reference application of specific countermeasures to various hazard and threat scenarios. The second line summarizes the physical vulnerabilities ("PV" in the tables) of the scenarios. The third line summarizes the operational vulnerabilities ("OV" in the tables) of the scenarios, and the fourth line summarizes the damage potential ("DP" in the tables) of a successful attack.

Countermeasure Type

In the first column, the countermeasures ("CMs" in the tables) are grouped into three categories:

- Minimum measures,
- Measures for an elevated threat level, and
- Permanent enhancements.

These categories were created on the basis of the current state of practice, the current method of thinking concerning physical security of a transportation asset, and a knowledgeable body of study concerning the physical and structural weaknesses of tunnel structures and systems.

Minimum Measures. This category refers to physical, permanent measures and temporary, operational measures that should already be in place in every tunnel. These measures may be required by local code or be widely accepted standard design and practice as designated by professional societies. The measures may represent the current state of practice in tunnel safety and security, born of lessons learned and a collective body of knowledge. The measures are above-average in efficiency and generally moderate in cost.

These measures include

- Lighting;
- Ventilation system;
- Fire detection system;
- Fire protection system;
- Closed-circuit television (CCTV) system or closed-circuit video equipment (CCVE);
- Security awareness training;
- Roving patrols;
- HazMat restrictions;
- Background checks (of employees and/or vendors);
- Access controls (bollards, fences, walls, locks);
- Employee identification system;
- Intrusion detection system;
- Evacuation protocols;
- Extend/heighten supply air intakes;
- Anti-virus software;
- Computer firewalls;
- Backup manual control of systems;
- Regularly scheduled data backup; and
- Full-scale emergency response exercises.

Measures for an Elevated Threat Level. These countermeasures are temporary, normally operational measures designed to be implemented when the tunnel system faces an elevated threat level. The threat level would ordinarily be based on the general location of the tunnel or an actual threat directed at the facility. Typically, the credibility of a threat to a tunnel or the surrounding area is assessed by a law enforcement or intelligence agency and passed through to the tunnel owner or operator.

The measures deployed under this category are operational. They largely consist of personnel-specific actions that can be deployed quickly across any area of the tunnel and kept in place as long as desired. The measures are also portable and can be ended quickly once the elevated threat condition has passed. The costs for implementing these temporary measures are variable and directly related to the level of increased presence and operations at the tunnel. The costs rise as the level of protection and the deployment durations increase.

Countermeasures that are deployed for an elevated threat level normally provide a measure of public assurance. This public assurance aids to temper any loss of mission due to increased travel times through the tunnel or inconvenience due to temporary changes of routine while transiting the tunnel.

Measures recommended for implementation during an elevated threat level include

- Guards at portals;
- Inspections (personal/vehicle/ship);
- Bomb-sniffing dogs;
- Onsite credential checks;
- Waterborne patrols;
- Ship-tracking protocols (in restricted areas);
- Explosive detectors—mobile; and
- C/B/R detectors—mobile.

Permanent Enhancements. This category includes all structural and system alterations of the tunnel environment that are added to increase the safety and security of the tunnel. Permanent enhancements are costly and require time to design and build. The sometimes significant alteration of the tunnel requires capital investment by the owner and cooperation of management to implement these measures.

Permanent enhancements will often serve the dual benefit of extending the usable life of the tunnel structure and support systems. The renovations and improvements to strengthen the structure or provide redundancy may decrease the need for future capital investment to mitigate the effects of use and age.

The recommended measures include the following:

- Explosive detectors—fixed;
- C/B/R detectors—fixed;
- Redundant ventilation systems;
- Interior liner steel plates or panels;
- Interior concrete panels;
- Interior concrete or chemical grouting;
- Exterior (ground) concrete or chemical grouting;
- Interior liner bolting or tie-backs;
- Rip-rap over tunnel;
- Precast concrete slab over tunnel;
- Interior roof steel plates;
- Interior roof panels;
- Exterior roof steel plates;
- Exterior roof concrete panels;
- Bollards to control access;
- Fencing to control access;
- Concrete encasement of columns;
- RFP wrapping of columns;
- Steel jacketing of columns;
- Redundant columns or walls;
- Floodgates; and
- Disperse functions (i.e., redundant systems).

Countermeasure Functions and Descriptions

The second column within each table describes the countermeasure and its function. The range of countermeasures explored in this guide track closely to the hazards and threats identified in Chapter 2. The countermeasure guides do not address weather induced hazard scenarios that are common in certain areas, such as blizzards and floods, because a tunnel owner or operator encountering serious weather events would already have a body of knowledge and practice that is best for the local situation. Patterns of weather induced disruptions to a tunnel, if any, have been set by history. In addition, countermeasures do not address weather events because such events cannot be deterred, deflected, or interdicted.

Each listed countermeasure represents a general class of measures, where appropriate. There is some latitude regarding which specific measure from the class will be implemented. For example, in the class of lighting, the system chosen could be high-pressure sodium, low-pressure sodium, incandescent, or any other type of fixture to provide illumination to a given area. The lighting may be mounted to a pole or wall or hung from a mast arm. The lighting system may be placed 20 to 50 feet (6 to 15 meters) apart, depending on the illumination requirements. The myriad of choices for the implementation may be settled only by a review of local conditions.

The countermeasures listed will lead the user to a subsection of measures for further exploration. The decision on which countermeasures should be implemented must be based on full knowledge of what currently exists in the tunnel environment, as well as what local conditions dictate.

Relative Effectiveness

The third column rates the relative effectiveness of the countermeasure as low (L), medium (M), or high (M). While the ratings assigned to the various countermeasures are based on many years of engineering expertise and past project experience, it must be pointed out that the rating system is subjective.

This rating gives the likely effectiveness of the recommended countermeasure to secure the asset, improve the safety of the asset, or mitigate the damage potential of a successfully delivered disruption. The rating scale indicates how useful the countermeasure would be as a single-source measure.

The effectiveness ratings are not intended to provide usefulness of each countermeasure coupled or installed in tandem with others that appear on Tables 34 through 41. The ratings for the effectiveness of each countermeasure are based on the collective experience of the research team and their combined 200+ years of tunnel design, construction, and operation. The ratings are also drawn from the experience gained in other, current work, including that performed on behalf of the U.S. Department of Homeland Security and several state and regional authorities.

Order-of-Magnitude Cost

The fourth column gives an order-of-magnitude cost ranging from low (L; up to $1 million) to very high (VH; over $10 million). Again, the cost ratings are very subjective and depend on a number of variables, including tunnel length, tunnel construction type, construction materials, surrounding earth geology and groundwater conditions, available clearances, and interruption of operations (e.g., lane closures, track outages, and disconnection of catenary and/or third rail power). The continuous operation of a facility is a primary goal of a tunnel owner or operator. Therefore, mitigation measures should be performed from the outside of the tunnel as opposed to the inside whenever possible to avoid interruption of ongoing operations.

The order-of-magnitude costs of countermeasures are given as general guidance only because the implementation of any countermeasure is subject to local variables that cannot be accounted for in this guide. The local variables could make the cost higher or lower than the cost estimate. Similarly, if the tunnel operations and maintenance staff have the capability to install or implement certain countermeasures, the overall cost to the owner would be significantly decreased.

The cost estimates are given in broad ranges to reflect the disparity in prices across the geographical areas of the 500+ tunnels in the United States. Labor costs, climate, equipment durability, and the purchasing power of the tunnel owner or operator can affect the prices paid to obtain the countermeasures. The ranges are wide to ensure the suitability of this report for a nationwide audience.

The cost estimates are based on reasonable assumptions of how many countermeasure items would likely be needed in a tunnel environment. Where possible, a direct comparison to a tunnel retrofit was applied. The collective experience of the research team was used in developing the cost estimates. The final cost of all countermeasures and mitigation would need to be established locally and be based on the actual conditions the tunnel owner or operator faces.

In Tables 34 through 41, the cost estimate indicators are as follows:

- Low (L)—Cost estimate to implement this countermeasure in a tunnel system should not exceed $1 million.
- Medium (M)—Cost estimate to implement this countermeasure in a tunnel system should range between $1 million and $3 million.
- High (H)—Cost estimate to implement this countermeasure in a tunnel system should range between $3 million and $10 million.
- Very high (VH)—Cost estimate to implement this countermeasure in a tunnel system should exceed $10 million.

Physical/Operational

The fifth column of Tables 34 through 41 indicates whether the countermeasure is a physical measure (P), an operational measure (Op), or both.

Physical measures are constructed or deployed in a set location and require some type of inspection, design, construction, and maintenance activities. Physical countermeasures require planning before deployment (such as preparation of design and construction documents) so as to maximize efficiency and value in serving the safety and security needs of the tunnel asset.

Operational measures use personnel and are flexible, dynamic to the fluidity of a hazard or threat, and mobile. Operational measures can be elevated or downgraded to match the level of hazard or threat anticipated.

Strategy

The sixth column of each table indicates the strategy or strategies of each countermeasure. The strategies have evolved and been refined over time in accordance with the work of the National Academy of Science, the U.S. Department of Homeland Security, and practitioners across the nation. The strategies are aligned with current thinking in the area of transportation risk and security, including the upcoming multimodal guide entitled, "Guide to Risk Management of Multimodal Transportation Infrastructure," which is being developed under NCHRP Project 20-59(17).

Possible strategies are deterrence (DR), detection (DT), interdiction (I), and mitigation (M; including response and preparedness):

- **Deterrence (i.e., Deflection):** This category identifies countermeasures with a sure strategic objective, namely making an asset so difficult to disrupt, or so costly to the intentional attacker, that any disruption is not attempted. This category may also include the owner or operators' ability to present their asset as impervious to intentional harm, such that the attacker is diverted to explore another target or not attack at all. The concept of deterrence is not usable against natural hazards. Hurricanes, blizzards, floods, and other acts of nature cannot be deterred from their natural course.
- **Detection:** This category identifies countermeasures in which the owner or operator can recognize that a hazard or threat exists and can communicate that actual or perceived hazard or threat to responders. This category applies to countermeasures implemented to learn of a disruptive event. The methods, techniques, technology, and personnel deployed to learn of a pending or actual incident may vary based on local conditions. The means of detection may range from the physical, including sensors and implanted devices, to the operational, including analysis of intelligence gleaned from various sources.

  The act of detection extends to natural disasters and other unintentional events as clearly as to events of nefarious origin. Use of technology to pinpoint an unusual weather event or a faulty pump that may flood a road is as applicable to detecting a hazard as the police officer on fixed post at the portal inspecting cargo and discovering an explosive. Each action is valid.
- **Interdiction:** This category identifies countermeasures in which the owner or operator can meet a hazard or threat after it has begun the delivery process. The owner or operator should have preestablished personnel and material resources that may immediately be deployed upon learning of the hazard or threat, which may be en route, at the target, or in the process of being delivered. Interdiction most normally applies to intentional acts of disruption, such as an attacker or saboteur entering the asset. Interdiction is a less significant strategy in dealing with natural weather events or spontaneous hazards, such as equipment fires.
- **Mitigation:** This category identifies countermeasures designed to lessen the damage potential of any successfully delivered hazard or threat. The wide-ranging measures that fall into this category include both *strategic mitigation measures* requiring forethought and planning and *tactical mitigation measures* conducted by on-scene responders.

  Strategic mitigation measures are long-range mitigation measures that require effort and resources well in advance of a potential or actual hazard or threat. These measures involve planning and preparation, which generally include

  – Institutional arrangements and plans or memoranda of understanding,
  – Communications or public outreach plans,
  – Interdiction plans for intentional acts,
  – Continuity of operations plan,
  – Emergency response and recovery plan,
  – Agency preparedness plan,
  – Agency mobilization plan,
  – Drill and exercise guide, and
  – Personal preparedness plans (for responding employees).

  Strategic mitigation measures with all of these components allow the tunnel operating agency to prepare and respond to any disruption as one unified body, so well-versed and well-practiced in the plans that it can take last-minute, on-the-spot actions.

  Strategic mitigation measures may also involve physically improving an asset so that it is impervious to the impact of the hazard or threat deployed. For example, reinforcing a tunnel with steel plates will make the tube better able to withstand a blast overpressure, fire, or derailed train. A full list of ideas to mitigate a hazard or threat by using physical improvements and design is discussed in Section 5.4.

  Tactical measures include an emergency response to the scene at the time of disruption. Rescuing people, diverting traffic, and activating backup equipment can restore the asset's operations. The ability to mitigate the damage potential of a hazard or threat by preparedness or response depends on the institution's ability to have well-planned, well-executed operational measures in place. These measures will likely include the involvement of personnel and agencies beyond the jurisdiction of the tunnel owner or operator. The need for advanced planning and tactical coordination is crucial for the success of this tool to be employed as a mitigating measure against all hazards and threats.

Some countermeasures have multiple strategies associated with them, such as bollards, which act as both deterrence and mitigation. Such countermeasures may receive higher priority for this dual benefit.

Multiple-Benefit Potential

Many countermeasures have potential to provide other benefits besides increasing the safety and security of a tunnel.

Multiple-benefit potential may change the prioritization of countermeasures. For example, some mitigation measures can both decrease maintenance and increase the usable life of the structure. This dual benefit could lead to significant cost savings over the life of the structure. The identification of multiple-benefit potential is based on realistic expectations of what may be done with the countermeasure, including the following potential benefits:

- Pedestrian safety,
- Traffic surveillance,
- Public assurance,
- Anti-theft,
- Anti-trespassing.
- Detection of unqualified employees,
- Decrease maintenance,
- Increase usable life of system,
- Erosion protection,
- Protection of data integrity,
- Protection of investment in data systems, and
- Dock scheduling (for shipping).

Countermeasure Number

The last column of the countermeasure guides identifies the countermeasure number. Countermeasures 1 to 19 are recommended minimum measures and are described in detail in Section 5.4.1. Countermeasures 20 to 27 are recommended measures for an elevated threat conditions and are described in detail in Section 5.4.2.

Countermeasures 28 through 50 are recommended permanent enhancements and are described in detail in Section 5.4.3.

5.3.3 How to Use the Countermeasure Guides

The following steps should be followed in using the countermeasure guides (Tables 34 through 41):

1. Review the tables to further eliminate certain hazards and threats based on existing knowledge or inspection of countermeasures that are already in place or not possible based on restrictions such as operating environments and clearances.
2. Identify all possible countermeasures for your facility, and make a list of countermeasure numbers from the last column of Tables 34 through 41 to be reviewed.
3. Study the relevant sketches and text in Sections 5.4.1, 5.4.2, and 5.4.3 to become familiar with the details involved.
4. Go back to Tables 34 through 41 to weigh relative effectiveness and order-of-magnitude costs of identified countermeasures.
5. Create a prioritized countermeasure list for your facility.
6. Consider multiple-benefit potential information to determine if your list should be re-prioritized.
7. Study again the relevant sketches and text in Sections 5.4.1, 5.4.2, and 5.4.3, and finalize your priority list.

If more detailed information than that provided herein is needed to justify a selection, an in-house or outside expert can be used to develop conceptual designs and associated costs of possible countermeasures.

The following abbreviations and cost scales have been used throughout Tables 34 through 41:

<u>Text Above Tables</u>
PV = Physical Vulnerability
OV = Operational Vulnerability
DP = Damage Potential of a Successful Attack

<u>Column 3: Relative Effectiveness</u>
L = Low
M = Medium
H = High
VH = Very High

<u>Column 4: Order-of-Magnitude Cost</u>
L = Low = up to $1 million
M = Medium = between $1 million and $3 million
H = High = between $3 million and $10 million
VH = Very High = over $10 million

<u>Column 5: P/OP</u>
P = Physical
Op = Operational

<u>Column 6: Strategy</u>
DR = Deter
DT = Detect
I = Interdict
M = Mitigate (Includes Response and Preparedness)

5.4 Countermeasure Descriptions

The following sections describe in detail the countermeasures listed in the countermeasure guides. Since the continuous operation of a facility is a primary goal of a tunnel owner or operator, each of these mitigation measures should consider the effect that construction will have on operations. In some cases, the cost of service interruption may outweigh the cost of construction. Whenever possible, construction should be performed from the outside of the tunnel as opposed to the inside to avoid interruption of ongoing operations. Other considerations should include dynamic clearance envelopes necessary for equipment types, methods of installation of countermeasures by contractors, presence of employees for maintenance and inspection, and use of the facilities by passengers during emergencies.

5.4.1 Recommended Minimum Measures

Countermeasure 1: Lighting

Lighting provides a basic, reliable, and cost-effective safety and security measure. By providing visibility to all critical areas, lighting enables a monitor, controller, or law enforcement official to take the necessary preventive actions to deter an intentional threat or to detect a disruption that is occurring or has occurred in the tunnel environment. In addition, proper lighting allows for the safe evacuation of impacted tunnel users and employees during an emergency, simultaneously assisting emergency responders arriving to the incident scene. This safe and efficient response is necessary for any disruption, intentional or unintentional, including natural disasters. See Table 42.

The cost of lighting schemes varies as a function of the level of illumination and the quality and quantity of lights installed. The mounting surface (i.e., wall or ceiling) will also affect the final cost. There are typical types of lighting fixtures and arrangements used in tunnel environments, and their proven histories can provide a reliable barometer for any new installation, upgrade, or retrofit.

Countermeasure 2: Ventilation System

The ventilation system is usually the most important life safety system in the tunnel. The type of ventilation system used in a tunnel can vary and is typically affected by the following:

- Tunnel mode or usage
  - Road
  - Transit
  - Passenger/freight rail
- Construction methodology
  - Immersed tube
  - Cut-and-cover
  - Bored or mined
  - Air-rights structures
- Tunnel attributes
  - Length
  - Shape
  - Occupancy loads
  - Location
- Date of initial construction
  - In some cases, very old tunnels reflect the state of ventilation technology at the time of construction

To provide the best applicable ventilation system, the tunnel owner or operator must conduct an examination of the current system, if installed, or as designed before construction. This examination needs to include deference to the uses of the ventilation system to support the safety of the tunnel environment. A well-designed, well-maintained ventilation system can provide the means to direct and exhaust smoke or fouled, toxic air away from tunnel users involved in an incident. The ventilation system effectively maintains or improves the safety of the tunnel. See Table 43.

Tunnel ventilation systems require capital investments as well as assiduous maintenance programs to ensure their effectiveness.

Table 42. Countermeasure 1: Lighting.

Countermeasure Description	Installed, well-sited lighting system designed to provide illumination to all areas of the tunnel environment.
Types/Components	High-pressure sodium; low-pressure sodium; incandescent; luminescent.
Use	Roadway lights; area lighting; security lighting; access area lighting.
Category	Minimum measures.
Strengths	Visibility in all areas.
Weaknesses	Susceptible to power failure from external utility; possible misapplication of light for color CCTV applications.
Rough Cost of Implementation	Medium—$1 million to $3 million per tunnel. Cost depends on tunnel length and type of fixtures.
Operation and Maintenance	Installation and maintenance may be handled in-house.
Training Requirements	None.
Life Expectancy	Infrastructure: 20+ years; Lamps: 24,000 hours.
Comments	Cost varies widely by system size and utility work required. Electrical costs and lamp replacements every 1 to 3 years. Standard electrician can maintain system.

Table 43. Countermeasure 2: Ventilation system.

Countermeasure Description	Provides airflow to and from the tunnel space.
Types/Components	Supply fans (blowers); exhaust fans; ducts; dampers; louvers; power source.
Use	Coverage of entire tunnel area.
Category	Minimum measures.
Strengths	Road tunnel systems can be used for non-emergency (i.e., normal) conditions to remove airborne impurities from the roadway.
Weaknesses	Requires sustained maintenance to maintain effectiveness.
Rough Cost of Implementation	Very high—over 10 million per tunnel. Cost depends on tunnel length and ventilation system type.
Cost of Operations and Maintenance	15–25 percent.
Training Requirements	High—initial training of control center and maintenance staff, followed by annual incremental refreshers and/or updates.
Life Expectancy	10–20 years.
Comments	Cost varies widely by system size and utility work required. Quality of system commensurate with cost. System may be upgraded from original, designed, and installed.

Countermeasure 3: Fire Detection System

Fire detection systems are sound investments for the safety and security of any tunnel system. An automated system capable of reaching all points within the tunnel environment will provide rapid notification of all smoke and flame conditions to a monitoring station, thereby triggering a rapid emergency response. See Table 44.

The smoke and flame conditions may be the result of unintentional events, such as malfunctioning equipment or vehicles. Smoke and flame may also be the result of a disruptive event such as a derailment, collision, or explosion. They may also indicate a breakdown of another crucial tunnel system, or a breach of the tunnel integrity.

Countermeasure 4: Fire Protection System

Tunnel fire protection systems can provide a quick response to a smoke or flame condition, protecting tunnel users and the integrity of the tunnel structure. The type of protection chosen and installed will depend on the tunnel usage. Whereas a wet system might be appropriate for a highway tunnel application, it would not be appropriate for an

Table 44. Countermeasure 3: Fire detection system.

Countermeasure Description	Provides a fixed, continually operating series of sensors to detect a conflagration.
Types/Components	Flame detectors (ultraviolet or infrared); smoke sensors (ionization or light); heat sensors; one-button call systems for tunnel users; video monitoring; power source.
Use	Coverage of entire tunnel area.
Category	Minimum measures.
Strengths	Provides a rapid means of notification to emergency responders that a fire or smoke condition exists in the tunnel environment. Installed system is always operational and connected to monitoring facilities.
Weaknesses	None.
Rough Cost of Implementation	Low—less than $1 million per tunnel. Cost depends on tunnel length.
Operation and Maintenance	Typically requires private contractor for monitoring and possible maintenance.
Training Requirements	Medium—initial training of control center and maintenance staff, followed by annual incremental refreshers and/or updates. System is intentionally automated.
Life Expectancy	10–20 years.
Comments	Costs vary widely by system size and utility work required. Quality and cost of systems are fairly standard across all tunnel systems.

electrified transit or electrified rail tunnel. The most common type of tunnel fire protection system is the manually operated wet or dry standpipe. Automatic systems such as sprinklers and deluge systems (water-based or foam-based) and water mist systems are used, but are uncommon, particularly in the United States, which presently has only three road tunnels that use these technologies. The predominant criticism is the limited effectiveness of these systems, particularly for tunnel fires that begin inside a vehicle (car or train). Such fires constitute the majority of tunnel fires. Sprinklers, which have fusible links, must be directly over the heat sources to work. Deluge and water mist systems have open heads, so a high temperature or flame condition somewhere in the tunnel will activate the entire zone. At best, the water will cool down the fire and help to prevent its spread. At worst, the water will create panic in the tunnel and/or weigh down the smoke from the fire, bringing it closer to tunnel users. Annex D in NFPA 502 [Ref. 5] contains more information on the use of sprinklers in road tunnels. See Table 45.

The general term "fire protection" sometimes includes systems, but may also include the establishment of permanent structures to aid in the evacuation and shelter of tunnel users in the event of an incident involving smoke or flame. The establishment of safe zones inside the tunnel, capable of providing shelter from the smoke, flame, and heat, can provide safety to tunnel users awaiting rescue by emergency responders. Clear evacuation routes with easy-to-understand diagrams and signage would similarly assist tunnel users in fleeing a hazard or threat.

Countermeasure 5: Closed-Circuit Television (CCTV) System or Closed-Circuit Video Equipment (CCVE)

CCTV systems or CCVE provide the ability for a monitor to see inside the tunnel through real-time images transferred along a secure pathway. The images are typically transmitted from cameras located at the tunnel portals or along the road or track bed to an operations control center, where the image is recorded or monitored by an operator. The CCTV or CCVE image may be shared with decision makers and emergency responders through a secure intranet. This technology is readily available and cost-effective. See Table 46.

This transmission of images conveys the information necessary for immediate and appropriate response to any incident scene (e.g., the safest path to approach and access the site, the conditions along the route, and what equipment and resources are required at the location).

Countermeasure 6: Security Awareness Training

Security awareness training provides a cornerstone of the owner or operator's efforts to form a culture in their agency for security to complement longstanding, prevalent efforts in improving safety. A well-grounded training program may aim to indoctrinate new employees and educate existing employees in their potential to be front line detectors of abnormal people or activity that may lead to any disruption of the tunnel system. See Table 47.

Providing employees with the proper tools to detect potential security threats, borne of insufficient internal procedures or external threats, enables the owner or operator to prevent a disruption from occurring. Training programs are generally cost-efficient and -effective. Employees typically retain the transferred knowledge, and the message is uniformly distributed to others. Training programs are flexible and can be altered to include new techniques and information as they develop. An effective training program should reflect the state of practice and the state of knowledge in the transportation and infrastructure security arena.

Table 45. Countermeasure 4: Fire protection system.

Countermeasure Description	Provides a fixed, continually operating series of distribution channels to combat a smoke or flame condition.
Types/Components	Wet standpipe; dry standpipe; sprinklers; deluge; water mist; fire extinguishers; evacuation pathways, cross-passages, and refuges; power source.
Use	Coverage of entire tunnel area.
Category	Minimum measures.
Strengths	Provides an immediate means of mitigating fire or smoke in the tunnel environment. Some installed systems can be automated.
Weaknesses	None.
Rough Cost of Implementation	High—between $3 million and $10 million per tunnel. Cost depends on tunnel length, system size, and utility work required.
Operation and Maintenance	Typically requires private contractor for maintenance.
Training Requirements	Medium—initial training of control center and maintenance staff, followed by annual incremental refreshers and/or updates.
Life Expectancy	10–20 years.
Comments	Quality and cost of systems are fairly standard across all tunnels.

Table 46. Countermeasure 5: CCTV System or CCVE.

Countermeasure Description	Provides a fixed, continually operating channel of video images to monitors and responders.
Types/Components	Cameras; monitoring stations; recording capacity; image-sharing capability; power source.
Use	Coverage of entire tunnel area.
Category	Minimum measures.
Strengths	Provides an immediate means of viewing conditions inside the tunnel environment using real-time video feed.
Weaknesses	Requires maintenance; systems can quickly become outdated.
Rough Cost of Implementation	Medium—between $1 million and $3 million per tunnel. Cost depends on tunnel length and coverage (i.e., number of cameras).
Operation and Maintenance	Maintenance may be handled by in-house personnel. Monitoring should be done by owner or operator's staff.
Training Requirements	Medium—initial training of control center and maintenance staff required, followed by annual incremental refreshers and/or updates.
Life Expectancy	5–10 years.
Comments	Quality and cost of systems are fairly standard across all tunnel systems.

Table 47. Countermeasure 6: Security awareness training.

Countermeasure Description	Modular based, instructor-led training program.
Types/Components	Module-based; initial training; annual refresher sessions.
Use	Required instruction for all tunnel employees.
Category	Minimum measures.
Strengths	Low-cost, effective method to teach all employees to be front line observers of unusual or suspicious behavior.
Weaknesses	Poor instruction may be transferred to employees. Quality control over instruction is necessary.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	None—measure is not mechanical.
Training Requirements	High—initial and refresher training of all employees is necessary.
Life Expectancy	2–5 years.
Comments	The use of external consultants with credentials in tunnel security training may be expedient to the owner or operator.

Countermeasure 7: Roving Patrols

Tunnel owners and operators may implement roving patrols to increase the level of safety and security vigilance. Patrols provide trained personnel, typically with police powers, to explore the areas in and around the tunnel structure and support systems. The patrol personnel can act immediately to investigate any unusual or suspicious situation and respond immediately to any hazard or threat. The usual staggered time delay associated with visits or rounds provides a layer of uncertainty to anyone intent on perpetrating an intentional threat. However, patrols are excellent resources to interdict a hazard or threat and to lead a response. See Table 48.

Roving patrols are flexible in application, and their numbers can be increased or decreased quickly to match any perceived or actual hazard or threat. This flexibility is unmatched in any other countermeasure and limited only by the number and availability of trained personnel. The training of patrol personnel can be as comprehensive as desired by the tunnel owner or operator.

Countermeasure 8: Hazardous Material (HazMat) Restrictions

A common existing practice among tunnel owners and operators is the restriction of hazardous materials from being transported through the tunnel structure. This measure is typically enacted to protect the tunnel from explosion or contamination that may be caused by an accident or spill. The measure is an effective and low-cost way to protect tunnel users from a potentially harmful disaster. See Table 49.

Restrictions on hazardous materials are generally adhered to in public-use tunnel systems, such as highway and transit.

Table 48. Countermeasure 7: Roving patrols.

Countermeasure Description	Mobile police or private security patrols moving in and around the tunnel structure.
Types/Components	Police; private security; mobile; trained.
Use	Coverage of all tunnel areas.
Category	Minimum measures.
Strengths	Trained; mobile; flexible; rapidly deployable.
Weaknesses	Cost for extended service.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	None—measure is not mechanical.
Training Requirements	High—specialized, intense training of police and security personnel is required.
Life Expectancy	2–5 years.
Comments	

Table 49. Countermeasure 8: HazMat restrictions.

Countermeasure Description	Restriction or exclusion of materials in the tunnel system.
Types/Components	Flammables; chemicals; corrosives; toxic; biological.
Use	Applicable to all tunnel areas.
Category	Minimum measures.
Strengths	Removes the hazard or threat from introduction into the tunnel, thereby eliminating a source of potential disruption.
Weaknesses	None to owner or operator.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	None—measure is not mechanical.
Training Requirements	Low—no special training is required for tunnel employees.
Life Expectancy	Lifetime.
Comments	Measure is flexible; more stringent standards may be implemented at short notice.

Restrictions on the transport of hazardous materials to ensure their safe handling and passage may be employed so as to allow their passage through freight tunnels. Additional restrictions or required processing procedures may slow the progress of acceptable hazardous materials through the tunnel, slowing commerce and perhaps having an economic impact on the community.

Restrictions on hazardous materials are flexible measures that can be intensified or implemented with increased standards during periods of elevated threat levels. In conjunction with vehicle inspections, hazardous material restrictions can be intensified to preclude materials from being transported through the tunnel to ensure that they cannot be used in an intentional attack.

Countermeasure 9: Background Checks

Tunnel owners and operators may conduct background checks of potential employees, vendors, and contractors. See Table 50.

Conducting background checks of potential employees is a common practice to ensure that a candidate is qualified and free of criminal or suspicious associations. The investigations conform to local law and policy, including employee collective bargaining agreements. Beyond the initial background investigation, updates are typically done for cause, without a set schedule.

Investigations of vendors and contractor personnel are uncommon at this time. However, such investigations would provide an extra measure of safety and security. If vendors and contractor personnel are routinely provided unfettered access to the tunnel environment for the purpose of construction, maintenance, or delivery, then they represent a weak link in the security perimeter for that tunnel system. This weak link is more acute if the vendors or contractors can access the tunnel without an escort from the owner or operator staff.

Investigations of employees, vendors, and contractors may be as involved as desired by the owner or operator and as allowed by local law. They can range from cursory credit examinations to full-length background checks. The cost is

Table 50. Countermeasure 9: Background checks.

Countermeasure Description	Examinations of the backgrounds of employees, vendors, and contractors to discern less-than-qualified individuals and obvious security risks.
Types/Components	Criminal database search; personal background investigation; credit evaluation.
Use	All new-hire employees, vendors, and contractors.
Category	Minimum measures.
Strengths	Reasonable cost to screen personnel with access to the tunnel system and discern questionable persons.
Weaknesses	Terms and restrictions may be subject to local law or collective bargaining agreements.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	Measure is not mechanical; however, database tracking of screened personnel must be kept current.
Training Requirements	Low—no special training required for tunnel employees.
Life Expectancy	Lifetime.
Comments	

moderate, requiring only the active resource of in-house personnel to perform the background investigations and to track the employees who have cleared this requirement. This measure is also flexible, can be implemented to various degrees of specificity, and implemented with short notice, providing it is permissible under local statute and policy.

Countermeasure 10: Access Controls (Bollards, Fences, Walls, Locks)

Access control devices can provide an increased measure of security to fixed installations. The devices may be designed and installed to refuse entry to persons or items to a fixed location or to provide verification of individuals or equipment entering that location. The devices can be further divided into two categories, personnel access control and location access control. See Table 51.

Personnel access control consists of systems that are designed and installed with the purpose of allowing only authorized persons into a facility. The facility is meant to be permeable. The access control devices authenticate users entering the fixed location by a variety of methods.

There are many types of personnel access control devices available, including key cards matched with employment records, verification codes entered manually against a stored database, and biometric devices that measure body features and match them to individuals.

Location access control devices are designed and installed to prevent all physical access near a location or into a facility. Location access control includes simple door locks, steel or concrete bollards, gates, hydraulic risers, and steel curtains.

All access control devices provide an increased measure of security, but they are not infallible. A door lock can de defeated by a duplicate key. A computerized control system

Table 51. Countermeasure 10: Access controls (bollards, fences, walls, locks).

Countermeasure Description	Installation of mechanical and electronic devices to prevent unauthorized entry to tunnel areas.
Types/Components	Bollards; fences; locks; card swipe readers; proximity cards.
Use	All critical areas of tunnel or tunnel property.
Category	Minimum measures.
Strengths	Proven and available technology to secure an area from casual intrusion.
Weaknesses	Systems can be defeated.
Rough Cost of Implementation	Low—less than $1 million. Cost of wall depends on height and length.
Operation and Maintenance	System requires regular maintenance.
Training Requirements	Low—no special training required for tunnel employees.
Life Expectancy	Lifetime.
Comments	

can be hacked, and overrides can be set in place. Physically, a bollard or fence can be overcome by a superior force exerting pressure. Access control designs can be flawed (allowing for a missing link of coverage) or poorly maintained (rendering them useless). Access control devices designed for a singular purpose and staff can be misapplied.

There are five basic types of walls:

- **The gravity wall** gets its stability entirely from the weight of masonry and any soil resting thereon. This wall must be of sufficient thickness to resist the forces acting on them without developing tensile stresses. Concrete gravity walls usually contain a nominal amount of reinforcement near the exposed surfaces to control temperature cracking.
- **The semi-gravity wall** has largely supplanted the gravity wall because it is more slender and thus uses less material. However, the semi-gravity wall requires more vertical reinforcement along the inner face and into the footings to resist the rather small tensile forces that develop in these locations.
- **The cantilever wall** is a very common type of wall that consists of a base slab and a stem that are fully reinforced to resist the moments and shears to which they are subjected.
- **The counterfort wall** consists of a relatively thin concrete slab that is supported by vertical counterforts connected to the base at intervals on the back side.
- **The crib wall** is usually formed by rectangular elements or cells stacked on top of one another and filled with soil.

Countermeasure 11: Employee Identification System

Another measure to prevent trespassing in the tunnel areas is the implementation of an employee identification system. The systems, now common in many workplaces, may include the use of photo identification or data codes assigned to each employee. To enter a work area, the employee would be required to display his or her identification and have it accepted by the security monitor or access control device. See Table 52.

Employee identification systems have proven to be as effective as their level of maintenance and upkeep. Many programs are deficient in tracking the employee throughout his or her work life and particularly deficient at repossessing and/or deactivating identification cards after employees are transferred to other assignments or after employees cease to work for the employer.

A highly evolved program should have measures, policies, and procedures in place to reclaim the identification cards of inactive employees and electronically deactivate their permission to enter tunnel work areas. This accountability loop will maintain the integrity of the employee identification system.

Countermeasure 12: Intrusion Detection System

Intrusion detection systems (IDSs) are technologically advanced means of monitoring entry across large areas using minimal resources. Recent advances in technology provide a wide array of choices for implementing this measure. Most IDSs are small, power-saving devices that are capable of being linked together and with central monitoring stations. An IDS may also be linked to video capabilities to activate a video feed when it is tripped. An array of beams, lasers, sensors, and alarms can be installed in any part of the tunnel environment. Application of this measure requires that the tunnel owner or operator perform a thorough assessment of the IDS needs and choose from the best affordable technology. The IDS may

Table 52. Countermeasure 11: Employee identification system.

Countermeasure Description	Use of photo or other identification to prove employees or vendors have permission to be on tunnel property.
Types/Components	Photo databases; proximity cards.
Use	All employees, contractors, and vendors.
Category	Minimum measures.
Strengths	Reasonable cost to provide a first, visible measure to discern trespassers.
Weaknesses	Terms and restrictions may be subject to contract or collective bargaining agreements. System can be defeated by forgery, or lack of database maintenance
Rough Cost of Implementation	Low—less than $1 million.
Operation and Maintenance	Measure is not mechanical, but database tracking of screened personnel must be kept current.
Training Requirements	Low—no special training required for tunnel employees.
Life Expectancy	Lifetime.
Comments	

be layered to cover essential control centers; mechanical and electrical equipment rooms; and vulnerable areas inside, above, and around the tunnel. This evaluation may require external expertise. See Table 53.

The amount of IDS equipment selected by the tunnel owner or operator will determine the total cost. Most IDSs require only standard maintenance and little more than a low-voltage power source.

IDS provides a strong link in the security posture against both the intentional threat, such as someone intent on causing disruption to the tunnel, and the unintentional hazard, such as a homeless person entering a mechanical room on a cold night.

Countermeasure 13: Evacuation Protocols

All tunnel systems may have, as a minimum, evacuation protocols designed to aid tunnel users in self-rescue and evacuation from an incident area before the arrival of emergency response personnel. Evacuation protocols typically consist of working plans and signage to direct tunnel users to pathways, dedicated stairwells, cross-passageways and, occasionally, shelter areas that are safe from smoke and fire. The relatively simple task of planning an evacuation is an effective, cost-efficient, and easy way to help an impacted tunnel user evacuate. See Table 54.

An effective evacuation protocol needs to be kept fresh and active through constant oversight, exercise, and updating. Many evacuation plans are distributed to the public and tunnel users in the form of leaflets or flyers.

Countermeasure 14: Extend/Heighten Supply Air Intakes

Newly constructed air intakes are accessible by height, by protective structures, or both. However, some existing air intakes must be retrofitted to remove the possibility of harmful substances or agents being introduced into the system. See Table 55.

There are various types of tunnel ventilation air intake structures. Road tunnels served by full transverse or semi-transverse supply systems typically house the fans and associated

Table 53. Countermeasure 12: Intrusion detection system.

Countermeasure Description	The installation of devices designed to provide notice when a person or item enters a specific area.
Types/Components	Beam; laser; sensor; alarm.
Use	Some or all tunnel access points.
Category	Minimum measures.
Strengths	Unstaffed, cost-effective means to monitor a large area with the least resources.
Weaknesses	Relies upon efficient maintenance to remain operational.
Rough Cost of Implementation	Medium—between $1 million and $3 million per tunnel. Cost depends on size of protected property.
Operation and Maintenance	High—system requires maintenance.
Training Requirements	None.
Life Expectancy	5–10 years.
Comments	

Table 54. Countermeasure 13: Evacuation protocols.

Countermeasure Description	Establishment of evacuation protocols that are well-known, exercised, and supported.
Types/Components	Plans; signage; public instruction; drills and exercises.
Use	In all areas of the tunnel.
Category	Minimum measures.
Strengths	Provides a means for tunnel users and employees to self-rescue.
Weaknesses	None.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	Low—signage and instruction need only to be updated.
Training Requirements	None.
Life Expectancy	20–25 years.
Comments	

Table 55. Countermeasure 14: Extend/heighten supply air intakes.

Countermeasure Description	Design and construct durable air intake structures of increased height to thwart intentional or unintentional interference with the airflow.
Types/Components	Shafts; fences; screens; ductwork.
Use	All air intake devices.
Category	Minimum measures.
Strengths	This measure is a one-time investment to protect the air intake structures.
Weaknesses	New design may eventually be overcome by circumstance or intentional act of disruption.
Rough Cost of Implementation	Medium—between $1 million and $3 million per tunnel. Cost depends on local conditions.
Operation and Maintenance	Medium.
Training Requirements	None.
Life Expectancy	20–40 years.
Comments	

equipment in large ventilation structures. The supply airflow travels through intake louvers into the supply air plenum and through dampers, fans, sound attenuators, and ductwork before entering the tunnel. This path typically dictates that the intake louvers be located on an upper floor of the building, even though this upper floor is relatively inaccessible to the public.

Transit systems, on the other hand, commonly have sidewalk gratings that serve to bring outside air into the system. These gratings can lead to tunnels or stations and can be used in natural (piston-action) or mechanical ventilation systems. In any case, these air intakes must be protected from tampering and harm. Retrofit designs include the construction of a vent shaft of sufficient height around the existing grating, the erection of fencing or some other permeable barrier at a sufficient distance from the existing grating, or the relocation of the grating via interior ductwork and/or structural elements.

Countermeasure 15: Anti-Virus Software

All tunnel system data networks must have programs to detect and eliminate computer-generated viruses. On a daily basis, hundreds of viruses, weak or virulent, will attempt to enter the data system, normally through an external data connection. These attempts, largely indiscriminate, must be thwarted at the point of entry (the external data connection). Intentional introduction of viruses from inside the network must also be prevented through a series of anti-virus measures to protect the data network from itself. See Table 56.

The installation of anti-virus software is a common practice for anyone who has a computer or uses a data network. The software is readily available and relatively inexpensive. The effectiveness of this countermeasure is very high if the software is backed by a program of updates and maintenance. Such a program is readily available from commercial

Table 56. Countermeasure 15: Anti-virus software.

Countermeasure Description	Install software designed to thwart the introduction of malicious software code into the data network of the tunnel owner or operator.
Types/Components	Software code.
Use	Entire data network.
Category	Minimum measures.
Strengths	This measure is an investment to protect the integrity of the data network.
Weaknesses	None.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	Low.
Training Requirements	None.
Life Expectancy	Virus code definitions need to be continually updated.
Comments	This countermeasure is readily available from vendors who can provide a reliable, continually updated product to the tunnel owner or operator.

vendors and typically included in the price of the software purchase.

Countermeasure 16: Computer Firewalls

A complementary layer of cyber security for the tunnel data network includes the installation of firewalls. Firewalls are cyber codes written to prevent unauthorized entry to parts of the data network. These virtual partitions will authenticate the privilege rights of people attempting to enter areas of the network and deny access to those who do not appear on a specified list. See Table 57.

Firewall software is frequently tied to anti-virus protection by commercial vendors. The cost is relatively low for the protection provided. The challenge to the tunnel owner or operator is to establish the policies and regulations that will determine where the firewalls should exist. The tunnel owner or operator needs to establish permission levels for employees and visitors and then match those levels to the order of information contained within the whole of the network.

Countermeasure 17: Backup Manual Control of Systems

The design of new tunnels and the retrofit of older systems should include options for manual operation of MEC systems, including those used for safety and security. Ventilation, lighting, pumps, and alarms should be capable of manual operation if their connections to the control center are breached. See Table 58.

This redundancy exists in many older facilities, where the equipment was originally designed and installed to be operated manually. Later, retrofit controls may have been added to allow remote monitoring and operation. These retrofits should not have interfered with the ability of staff to manually throw a lever or a switch. Power sources to operate the systems should also be redundant. This may be accomplished through a dual feed or battery backup.

The design of some newer tunnel systems may have eliminated manual control of MEC systems, relying instead on the technology available to allow remote or automated control. If this is the case, efforts should be made to restore local, manual control of these support systems to provide the tunnel owner or operator with important redundancy. This advance planning will ensure safe and continuous operation if the data connection is disabled or destroyed.

Countermeasure 18: Regularly Scheduled Data Backup

All data networks should be duplicated regularly to protect against loss of information. These backups should be done to a server in a remote location from the main data processing center. The different locations lessen the risk that both primary and secondary data collection centers will be disabled by a localized event. Commercial services provide remote location data backups at a reasonable cost. See Table 59.

The owner or operator will need to determine the when and how often data should be backed up, as well as which pieces of information should be copied. The remote backups may be done on any schedule, but should be no less often than once per day. The selected data may include financial, operational, and/or transaction information.

Table 57. Countermeasure 16: Computer firewalls.

Countermeasure Description	Install software designed to partition the data files of the tunnel owner or operator and allow only authorized access to the file compartments.
Types/Components	Software code.
Use	Across entire data network.
Category	Minimum measures.
Strengths	This measure is an investment to protect the integrity of the data network and halt unauthorized access.
Weaknesses	None.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	Low.
Training Requirements	None.
Life Expectancy	Firewall settings and protection codes require regular maintenance and update.
Comments	This countermeasure is readily available from vendors who can provide a reliable, continually updated product to the tunnel owner or operator.

Table 58. Countermeasure 17: Backup manual control of systems.

Countermeasure Description	Design of switches, levers, and other manual devices to allow onsite control of support systems if the communication link to the operations center is breached. These manual control facilities should be at the site of support systems or near to the site of support systems.
Types/Components	Switches; levers; buttons.
Use	Critical support systems.
Category	Minimum measures.
Strengths	This measure provides a redundancy to the operation of the support systems. The manual controls enable the operation of the systems despite loss of central control and/or power.
Weaknesses	None.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	High—the systems machinery must always be kept in ready condition.
Training Requirements	High—tunnel staff need to be trained to operate the systems manually.
Life Expectancy	20–40 years.
Comments	

Table 59. Countermeasure 18: Regularly scheduled data backup.

Countermeasure Description	Program to duplicate data from network and then store that copy offsite. The offsite location should be at a distance from the main tunnel network system and have an independent power supply.
Types/Components	Software code.
Use	Across entire data network.
Category	Minimum measures.
Strengths	This measure is an investment to protect the integrity of the data network and mitigate any catastrophic loss due to hazard or threat.
Weaknesses	None.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	Low.
Training Requirements	None.
Life Expectancy	The data backups should be done on frequent intervals.
Comments	This countermeasure is readily available from vendors who can provide a reliable, continually updated service to the tunnel owner or operator.

Countermeasure 19: Full-Scale Emergency Response Exercises

At a minimum, every tunnel owner or operator should have a set of emergency response procedures and an emergency response plan (ERP) to address all potential emergencies at the facility. This plan should be based on recommendations and standards developed by organizations such as the NFPA and the World Road Association (PIARC). On a biannual or annual basis, full-scale emergency response exercises should be conducted at the tunnel to practice the procedures set forth in the ERP. These exercises should include tunnel operators; tunnel users (actual or staff); and all possible emergency response personnel, including firefighters, paramedics, and police. The simulated emergencies should vary from exercise to exercise, and participants should be unaware of the schedule to measure true preparedness. See Table 60.

5.4.2 Recommended Measures for an Elevated Threat Level

Countermeasure 20: Guards at Portals

A common practice among tunnel owners and operators during periods of elevated threat is to place fixed security posts at the tunnel portals to monitor people and traffic, to conduct inspections, and to be onsite to lead a response in the event of an incident that disrupts the normal mission of the tunnel. This measure is effective and adds a layer of deterrence to any person contemplating an intentional disruption, a layer of

Table 60. Countermeasure 19: Full-scale emergency response exercises.

Countermeasure Description	Program to conduct regularly scheduled, full-scale emergency response exercises.
Types/Components	Module-based; initial training; refresher sessions.
Use	Required practice for all tunnel employees and emergency responders.
Category	Minimum measures.
Strengths	Low-cost, effective method of teaching tunnel employees and emergency responders how to handle various tunnel emergencies.
Weaknesses	None.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	None—measure is not mechanical.
Training Requirements	High—initial and refresher training of all employees is necessary.
Life Expectancy	2–5 years to properly train newly hired employees.
Comments	

detection of threats, a layer of interdiction to parry a threat in the process of being delivered to the tunnel, and a layer of onsite mitigation to any successfully delivered threat. This measure, similar to that of roving patrols, is very flexible and rapidly deployable under any condition. The cost of the measure is commensurate with the length of time the post is fixed at the portal. If the post is not fixed at the portal under normal operating conditions, then additional personnel and resources must be obtained to staff the countermeasure. See Table 61.

Countermeasure 21: Inspections (Personal/Vehicle)

Inspections of both vehicles (including cargo) and persons are efficient measures of tracking who and what is entering the tunnel and to interdict potential hazards and threats. Establishment of the inspection cordon may deter people from perpetrating an intentional disruption and provide a means of detecting intentional or unintentional hazards and threats. Inspections provide a layer of screening, thereby decreasing the chance of a hazard or threat being successfully delivered. This countermeasure typically inspires public confidence in the overall security posture of the tunnel and limits the decrease in tunnel use. See Table 62.

The specific vehicles or vessels to be searched will be determined by the owner or operator in conjunction with law enforcement and will be based on their combined intelligence. In each jurisdiction, law enforcement will be the authority vested with the power to conduct the inspections. Vessels may appear on suspicion lists because of ownership, cargo, origin, or destination. Vessels with a measure of risk

Table 61. Countermeasure 20: Guards at portals.

Countermeasure Description	Placement of trained police or security guards in fixed posts at the portals of tunnel structures to inspect machinery and items entering the tunnel and to observe all activities occurring in and around the portal.
Types/Components	Police; private security.
Use	Fixed posts must be placed at each portal.
Category	Measures for an elevated threat level.
Strengths	Provides a thorough screening of all persons and material entering the tunnel through the portals. The use of trained police or security allows flexibility and rapidity of deployment.
Weaknesses	Potentially expensive.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	None—measure is not mechanical.
Training Requirements	High—each police officer or security guard placed at the portal needs to be highly trained to spot potential threats and to respond to confirmed threats.
Life Expectancy	Short-term duration, equal to elevated threat condition.
Comments	

Table 62. Countermeasure 21: Inspections (personal/vehicle).

Countermeasure Description	The implementation of a system to inspect all persons and vehicles (including cargo) entering a tunnel structure.
Types/Components	Vehicle; ship; persons; cargo; automated inspection; hand inspection.
Use	Inspection system must be applied at all entry points to ensure equal application.
Category	Measures for an elevated threat level.
Strengths	Properly applied, inspection system should ensure that hazardous items are kept out of the tunnel.
Weaknesses	Greatly increases costs to shippers that use the tunnel system, and decreases the flow of traffic through the tunnel.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	Use of automated inspection device, such as a scanner, will require external vendors and maintenance.
Training Requirements	High—each screener placed at the portal needs to be highly trained to spot potential hazards and threats and to respond to confirmed hazards and threats.
Life Expectancy	Short-term duration.
Comments	

toward the tunnel may be excluded from passing near or over the subaqueous structure.

Implementation of this inspection measure may require the installation of specialized machinery and/or the addition of personnel who are trained and legally authorized to conduct inspections. There is a cost associated with these deployments, some of which may be offset by the use of existing, in-house resources. Total outlays must include staffing costs, thereby having a variable cost element. The tunnel may also lose users to other transportation assets if the suitability of a replacement is deemed viable to the delays associated with the inspections being conducted at the portals. The longer the inspection measure is deployed, the higher the cost will be to the owner or operator. The economic cost to the public may also increase as the shipment of goods becomes delayed.

The inspection measure is most effective when coupled with a viable method to determine which persons or vehicles to inspect. An unfounded, blanket inspection ritual may not be as effective as a measured one based on sound assumptions. To achieve the proper mix, tunnel owners/operators are encouraged to tailor their inspection methodology and surrounding protocols to local applicable conditions.

Countermeasure 22: Bomb-Sniffing Dogs

Another common, existing practice among tunnel owners and operators is to conduct sweeps of the tunnel areas in search of explosives. A persistent program of frequent visits will decrease the opportunity for an aggressor to leave explosives within or near the tunnel. Deployment of bomb-sniffing dogs can be expanded to tunnel portals, support facilities (such as electrical substations), and nearby docks and marine facilities. The origin of an explosive threat will be outside the tunnel, allowing a sufficient window of opportunity for detection. The K-9 approach may also serve as an effective deterrent. Because of the success rate of dogs detecting even the faintest traces of explosives, an aggressor could anticipate that his or her attempt to move or plant an explosive would fail with this countermeasure in place. See Table 63.

A trained K-9 is very effective at detecting explosives and can be deployed and moved rapidly to a specific location. The K-9 program requires ongoing costs and maintenance to keep and train the dogs. A dog can typically only work for 3 to 5 hours a day and has a service life of only 4 to 5 years. Therefore, there is a continual need to resupply K-9 units to maintain effectiveness.

Countermeasure 23: Onsite Credential Checks

During periods of elevated threat, a heightened security posture may include implementation of a credentials check on jobsites. The check would focus particularly on areas of active construction or rehabilitation. A guard or similarly recognized individual would inspect the credentials of each person entering the site. The credentials would likely include a photo identification issued by the tunnel owner or operator that is valid for certain periods of time. See Table 64.

Countermeasure 24: Waterborne Patrols

When a tunnel crosses below a navigable waterway, waterborne patrols may be instituted in response to an elevated

Table 63. Countermeasure 22: Bomb-sniffing dogs.

Countermeasure Description	Using mobile canines to detect explosives in the tunnel.
Types/Components	Police; security.
Use	Throughout tunnel system.
Category	Measures for an elevated threat level.
Strengths	Very flexible in deployment schemes. K-9 is very effective in detecting explosives.
Weaknesses	Limited by availability of trained dogs.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	None—measure is not mechanical.
Training Requirements	High—each K-9 handler and dog requires specialized, in-depth training.
Life Expectancy	2–5 years.
Comments	

Table 64. Countermeasure 23: Onsite credential checks.

Countermeasure Description	Credential checks on each jobsite entrance.
Types/Components	Employees; contractors; photo identification.
Use	At the entrance to all jobsites.
Category	Measures for an elevated threat level.
Strengths	Ensures that unauthorized individuals are not permitted onto a site.
Weaknesses	None.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	Low—no mechanization.
Training Requirements	Medium—guard or checker must be trained to recognize a valid credential and to interdict a false identification.
Life Expectancy	1 year.
Comments	

threat condition. Waterborne patrols over the footprint of the tunnel elevate the security posture of the tunnel by providing a flexible deterrence, detection, and interdiction force at a major access point to the tunnel structure. Waterborne patrols can be tasked to conduct inspections of vessels crossing the footprint or to halt traffic into the same area. They can be deployed based on timeframes of expected vessel traffic or can maintain a fixed post. The use of waterborne patrols in the area over the tunnel footprint is effective in securing that area. See Table 65.

The cost of this measure includes the capital investment of a boat and the variable costs associated with operating and maintaining the boat as well as a trained crew. Maintenance costs will depend on the amount of time for which the boat is used. The sum of the costs depends on how often this measure is deployed in response to an elevated threat level.

Countermeasure 25: Ship-Tracking Protocols

A longer, strategic measure conducted in advance of, in place of, or in conjunction with waterborne patrols may be the institution of ship-tracking protocols in navigable waterways above a tunnel footprint. These protocols will allow the tunnel owner or operator to have input into the restrictions placed on vessels transiting the area. Content, speed, and time of crossing may be regulated. These regulations would require the tunnel owner or operator to work with the U.S. Coast Guard, which maintains jurisdiction over navigable waterways. The effectiveness of the protocols depends on the enforcement. Widespread adherence to the protocols may allow easier detection and, therefore, interdiction of a noncomplying transiting vessel. See Table 66.

Implementation of this countermeasure would require substantial resources and time to gain the voluntary acquiescence of local shippers and users of the waterway. Cost variables would also include software and tracking devices.

Countermeasure 26: Explosive Detectors—Mobile

Mechanical devices with the intent of detecting explosives within the tunnel environment may be deployed in a mobile, tactical manner for use at several locations. See Table 67.

Mobile detectors have many of the same capabilities and limitations as fixed detectors. Their chief advantage is the

Table 65. Countermeasure 24: Waterborne patrols.

Countermeasure Description	Deploy mobile, boat-based patrols to monitor boat traffic over an underwater tunnel crossing.
Types/Components	Mobile boat based.
Use	Use for water crossings only.
Category	Measures for an elevated threat level.
Strengths	Provides an active presence to the waters above a tunnel. Particularly useful in protecting tunnels under navigable waterways.
Weaknesses	May not be able to stop a suicide attacker intent on scuttling the boat.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	High—boats require specialized maintenance.
Training Requirements	High—personnel on patrol boats require specialized training to operate boat, board, or other vessels and to conduct interdiction activities. These personnel are likely drawn from law enforcement and must be authorized to conduct waterborne searches.
Life Expectancy	Short-term duration to match escalated threat level.
Comments	

Table 66. Countermeasure 25: Ship-tracking protocols.

Countermeasure Description	Establishment of restrictions for any vessel transiting the waterway above a tunnel footprint. This action may require the coordination of nearby docks and water users.
Types/Components	Water areas above tunnel footprint.
Use	Use for water crossings only.
Category	Measures for an elevated threat level.
Strengths	Provides a standard-use pattern for vessels to transit the area above the tunnel. The restrictions should prevent vessels from stopping or staging above the tunnel.
Weaknesses	May hamper shipping patterns in area. Also, spotlights vulnerable location.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	High—boats require specialized maintenance.
Training Requirements	Medium—a high level of coordination must occur.
Life Expectancy	Continual use of restrictions.
Comments	

ability to be deployed at different locations based on changing threat levels. However, these detectors require increased maintenance.

Countermeasure 27: C/B/R Detectors—Mobile

C/B/R detectors provide a means to detect C/B/R materials before they enter the tunnel environment. The C/B/R detectors can be located on mobile units for easy deployment. The C/B/R detectors may use the current technologies available and may contain sensors to detect individual materials. See Table 68.

The C/B/R measure requires a capital investment, specialized handling of the machinery, and training for those operating the systems.

5.4.3 Recommended Permanent Enhancements

Countermeasure 28: Explosive Detectors—Fixed

Mechanical devices with the intent of detecting explosives within the tunnel environment may be fixed and installed at tunnel perimeters and entrances. See Table 69.

Table 67. Countermeasure 26: Explosive detectors—mobile.

Countermeasure Description	Implementation of fixed or mobile explosive detection devices in and around the tunnel area.
Types/Components	Fixed and mounted inside tunnel structure or mobile and moved by mechanical means.
Use	At tunnel portals or inside traffic areas.
Category	Measures for an elevated threat level.
Strengths	Provides a measure of detection to find explosives in the tunnel.
Weaknesses	Detection devices may be impaired by the harsh environment of most tunnels. The systems may be impacted by dirt, grime, and poor air quality.
Rough Cost of Implementation	Low—less than $1 million per mobile unit. Medium—between $1 and $3 million per fixed unit.
Operation and Maintenance	High—units require specialized maintenance.
Training Requirements	Medium—supplemental training is required.
Life Expectancy	5–10 years.
Comments	New technology with increasing reliability is continually being researched and designed. Improvements to reliability and durability are in the future.

Table 68. Countermeasure 27: C/B/R detectors—mobile.

Countermeasure Description	Install sensors at tunnel portals to provide notification of C/B/R material entering the tunnel. The detectors provide a means to detect and interdict the material.
Types/Components	Chemical; biological; radiological.
Use	Located at portals.
Category	Measures for an elevated threat level.
Strengths	Provides a measure of detection and interdiction of C/B/R material.
Weaknesses	Current technology is imperfect.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	High—machinery and detectors require specialized maintenance and handling.
Training Requirements	Medium—technicians or personnel operating the detectors require specialized training.
Life Expectancy	5–10 years.
Comments	

The fixed explosive detector typically consists of a mechanical device that extracts air samples and, using a variety of means, tests them for explosive residue. Some models are capable of performing the test immediately, and others rely on a technician removing the sample and conducting the detection test in another location. The fixed detector relies on the extraction of air samples that are clean enough to be tested. Impurities that may contaminate the air sample must be low to allow a true measure of explosive residue to be detected. Foul air or clogged intake lines can alter the integrity of the explosive detection test. Fixed detectors are designed to mechanically emulate the chemical sensing abilities of a dog. Explosive detectors are not guaranteed to prevent the entry of explosives, and this technology is continually being reworked.

Countermeasure 29: C/B/R Detectors—Fixed

C/B/R detectors provide a means to detect C/B/R materials before they enter the tunnel environment. The C/B/R detectors can be permanently installed. The C/B/R detectors may use the current technologies available and may contain sensors to detect individual materials. See Table 70.

The C/B/R measure requires a capital investment, specialized handling of the machinery, and training for those operating the systems.

Countermeasure 30: Redundant Ventilation Systems

To ensure an adequate supply of fresh air to the tunnel and the exhaust of contaminated, foul, or smoke-filled air

Table 69. Countermeasure 28: Explosive detectors—fixed.

Countermeasure Description	Implementation of fixed or mobile explosive detection devices in and around the tunnel area.
Types/Components	Fixed and mounted inside tunnel structure or mobile and moved by mechanical means.
Use	At tunnel portals or inside traffic areas.
Category	Measures for an elevated threat level.
Strengths	Provides a measure of detection to find explosives in the tunnel.
Weaknesses	Detection devices may be impaired by the harsh environment of most tunnels. The systems may be impacted by dirt, grime, and poor air quality.
Rough Cost of Implementation	Low—less than $1 million per mobile unit. Medium—between $1 million and $3 million per fixed unit.
Operation and Maintenance	High—units require specialized maintenance.
Training Requirements	Medium—supplemental training is required.
Life Expectancy	5–10 years.
Comments	New technology with increasing reliability is continually being researched and designed. Improvements to reliability and durability are in the future.

Table 70. Countermeasure 29: C/B/R detectors—fixed.

Countermeasure Description	Install sensors at tunnel portals to provide notification of C/B/R material entering the tunnel. The detectors provide a means to detect and interdict the material.
Types/Components	Chemical; biological; radiological.
Use	Located at portals.
Category	Permanent enhancements.
Strengths	Provide a measure of detection and interdiction of C/B/R material.
Weaknesses	Current technology is imperfect.
Rough Cost of Implementation	Low—less than $1 million per tunnel.
Operation and Maintenance	High—machinery and detectors require specialized maintenance and handling.
Training Requirements	Medium—technicians or personnel operating the detectors require specialized training.
Life Expectancy	5–10 years.
Comments	

during an incident, the tunnel owner or operator may wish to install a redundant ventilation system. The system may be designed and built to supply air to and/or exhaust air from specific critical areas, evacuation shelters, and pathways or to ventilate air throughout the entire tunnel structure. The redundant system may be designed to operate independently of the main ventilation system, with a different power source and air source. Both systems will be controlled from a control station located outside the tunnel. The system may provide pressurized stairwells and evacuation zones dictated by local code or installed as part of original design for newer assets. Existing structures or systems may sometimes be used to reduce the cost of installation. See Table 71.

A redundant ventilation system requires a significant capital investment by the tunnel owner or operator. The effectiveness of the redundant system relies on a commitment to maintaining the system and testing its functionality at regular intervals.

Countermeasure 31: Interior Liner Steel Plates or Panels

The thickness of the steel plates or energy-absorbing steel panels will depend on the specific tunnel construction type, the construction materials (concrete, brick, etc.), the surrounding soil or earth geology, the groundwater conditions, the size of the IED or fire being considered, and the proximity of the hazard or threat to the liner. See Figure 15.

Table 71. Countermeasure 30: Redundant ventilation systems.

Countermeasure Description	Establishment of redundant ventilation to be used to supply fresh air and remove impure air in an emergency condition if the main ventilation system is not available.
Types/Components	Supply fans (blowers); exhaust fans; ducts; dampers; louvers; power source; backup power source.
Use	Installation to provide redundancy to critical tunnel areas, including evacuation routes.
Strengths	Provides redundancy to airflow systems.
Weaknesses	Requires high level of maintenance.
Rough Cost of Implementation	High—over $10 million per tunnel. Cost depends on tunnel length, ventilation system type, and scope of redundant system.
Operation and Maintenance	High—system must be kept in constant state of readiness.
Training Requirements	None.
Life Expectancy	20–25 years.
Comments	

Constructability issues include the following:

- Interior clearances for installation of steel plates or energy-absorbing panels.
- Work hours (weekdays, nighttime, and weekends); required track outages or highway lane closures.
- Limited number of crews per shift due to space constraints.
- Access to tunnel (personnel, equipment and material).
- Contractor staging area outside of tunnel.
- Work trains for rail tunnels; portable platforms for highway tunnels.
- Protection services for contractors (i.e., flagging); safety training for employees.

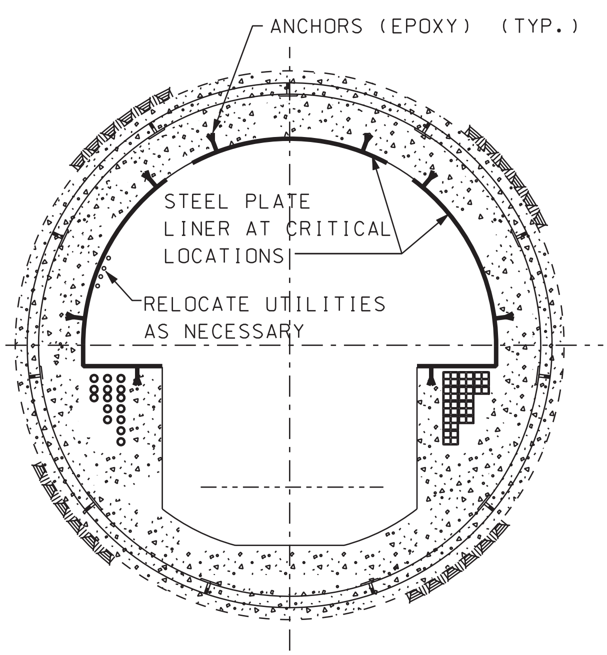


Figure 15. Interior liner steel plates or panels.

Countermeasure 32: Interior Liner Concrete Panels

The thickness of the precast or cast-in-place concrete panels will depend on the specific tunnel construction type, the construction materials (concrete, brick, etc.), the surrounding earth geology, the groundwater conditions, the size of the IED or fire being considered, and the proximity of the hazard or threat to the liner. See Figure 16.

Constructability issues include the following:

- Interior clearances for installation of concrete panels.
- Work hours (weekdays, nighttime, and weekends); required track outages or highway lane closures.
- Limited number of crews per shift due to space constraints.
- Access to tunnel (personnel, equipment, and material).
- Contractor staging area outside of tunnel.

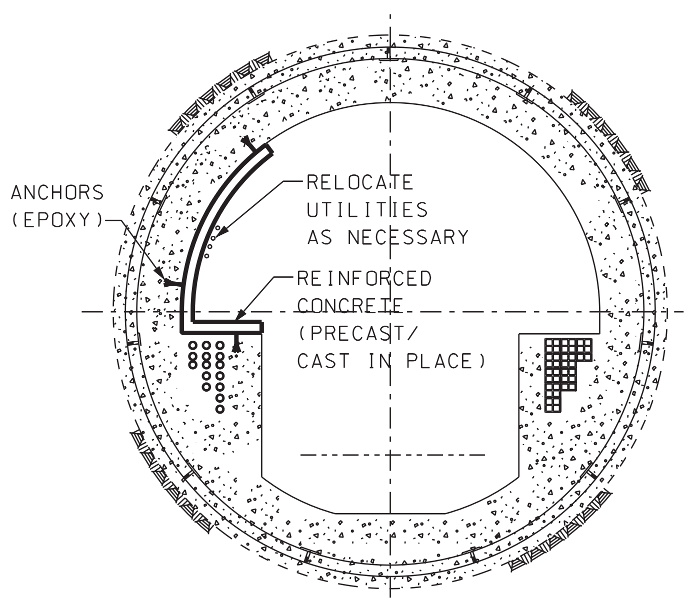


Figure 16. Interior liner concrete panels.

- Work trains for rail tunnels; portable platforms for highway tunnels.
- Protection services for contractors (i.e., flagging); safety training for employees.

Countermeasure 33: Interior Concrete or Chemical Grouting

To provide more strength for existing tunnels within the zone influenced by the hazard or threat of explosion or fire, and to overcome problems associated with these hazards and threats, a variety of protective systems can be applied. These protective systems include ground treatment measures such as cement-rich concrete and chemical grouting, which enable the tunnel liners to withstand higher forces. However, grouting mechanisms are difficult to verify and site-specific geotechnical information varies from project to project. See Figure 17.

Constructability issues include the following:

- Work hours (weekdays, nighttime, and weekends); required track outages or highway lane closures.
- Limited number of crews per shift due to space constraints.
- Access to tunnel (personnel, equipment, and material).
- Contractor staging area outside of tunnel.
- Work trains for rail tunnels; portable platforms for highway tunnels.
- Protection services for contractors (i.e., flagging); safety training for employees.

Countermeasure 34: Interior Liner Bolting or Tie-Backs

Another method of strengthening the tunnel liner is to use bolting or tie-backs with wire mesh and to apply shotcrete over it. The suitability of this method depends greatly on the surrounding geology. For example, this method is very effective for strong to medium rock types, but not for medium to weak rock types. See Figure 18.

Constructability issues include the following:

- Interior clearances for installation of bolting or tie-backs, wire mesh, and shotcrete.
- Work hours (weekdays, nighttime, and weekends); required track outages or highway lane closures.
- Limited number of crews per shift due to space constraints.
- Access to tunnel (personnel, equipment, and material).
- Contractor staging area outside of tunnel.
- Work trains for rail tunnels; portable platforms for highway tunnels.
- Protection services for contractors (i.e., flagging); safety training for employees.

Countermeasure 35: Exterior (Ground) Concrete or Chemical Grouting

Grouting mechanisms are difficult to verify, and site-specific geotechnical information varies from project to

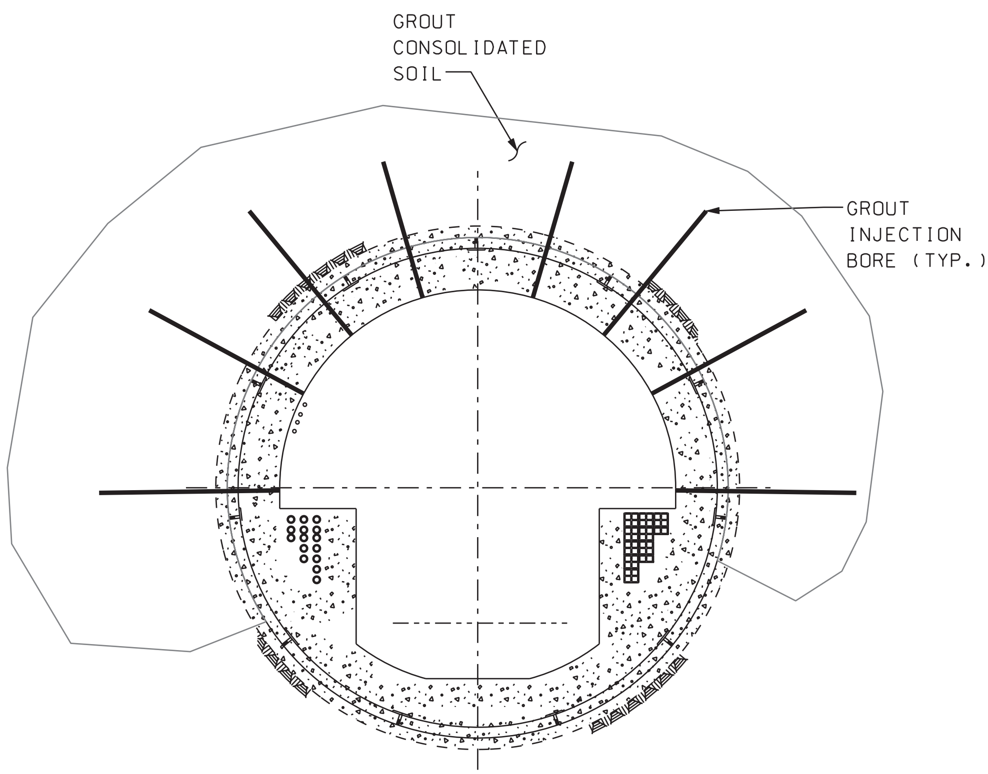


Figure 17. Interior concrete or chemical grouting.

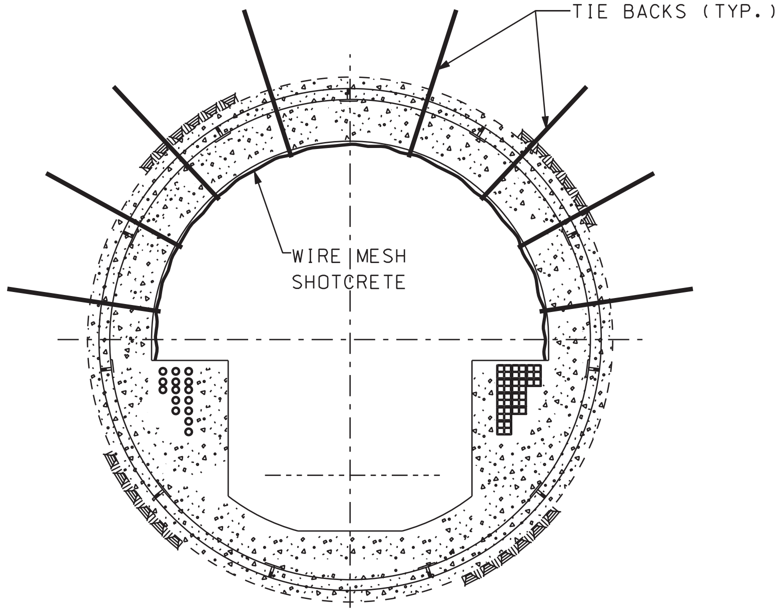


Figure 18. Interior liner bolting or tie-backs.

project. To provide more strength for existing tunnels within the zone influenced by the hazard or threat of explosion or fire, and to overcome problems associated with these hazards and threats, a variety of protective systems can be applied. These protective systems include ground treatment measures (such as cement-rich concrete and chemical grouting), which enable the tunnel liners to withstand higher forces. See Figure 19.

Constructability issues include the following:

- All work is conducted outside of the tunnel.
- The interior of the tunnel must be monitored by employees or expert contractors to ensure that the grouting process is not negatively impacting the tunnel.
- Depending on the land use above,
  - Permits may be required from the agency owning the land of the grout injection sites,
  - Coordination with other agencies may be required,
  - Utility relocation and coordination may be required, and/or
  - Work hours may depend solely on the contractor's schedule.

Countermeasure 36: Rip-Rap over Tunnel

Rip-rap can consist of stones, blocks of concrete, or other similar material. It is laid on the bottom of a water body, such as a river bed or stream, to protect the tunnel below from threats such as large IEDs or explosive containers dropped from a passing ship. See Figure 20.

Constructability issues include the following:

- Material is delivered via barge and lowered by cranes.
- Environmental issues require permits and approval from responsible agencies.
- Coordination with water traffic authorities is required.
- All work is conducted outside of the tunnel.

Countermeasure 37: Precast Concrete Slab over Tunnel

Similar to rip-rap, the precast concrete slab is laid on the bottom of a water body, such as a river bed or stream, to protect the tunnel below from threats such as large IEDs or explosive containers dropped from a passing ship. The thickness of the slab should depend on the size of the IED being considered and the amount of cover over the tunnel. However, the ground geology and the structural capacity of the tunnel may limit the amount of weight that can be added and, thus, must be taken into consideration. See Figure 21.

Constructability issues include the following:

- Material is delivered via barge and lowered by cranes. The size of the concrete segments depends on the capacity of the crane.
- Environmental issues require permits and approval from responsible agencies.
- Coordination with water traffic authorities is required.
- All work is conducted outside of the tunnel.

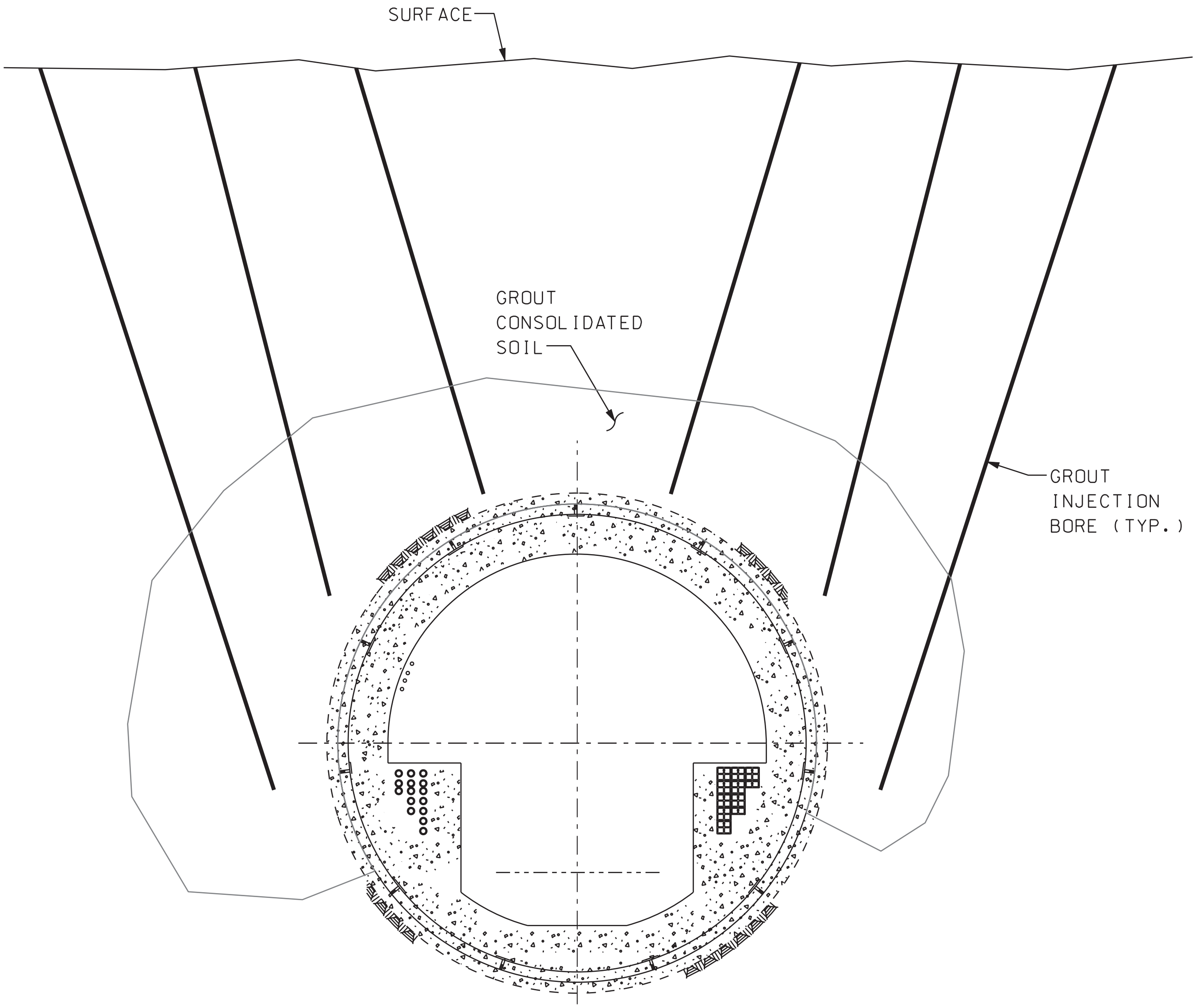


Figure 19. Exterior (ground) concrete or chemical grouting.

Countermeasure 38: Interior Roof Steel Plates

Interior roof steel plates are appropriate only for flat-topped, cut-and-cover tunnels. The thickness of the steel plates will depend on the available clearances, the tunnel construction materials (concrete or brick), the depth of cover over the tunnel, the surrounding soil or earth geology, the groundwater conditions, the size of the IED or fire being considered, and the proximity of the hazard or threat to the liner. See Figure 22.

Constructability issues include the following:

- Interior clearances for installation of steel plates.
- Work hours (weekdays, nighttime, and weekends); required track outages or highway lane closures.
- Limited number of crews per shift due to space constraints.
- Access to tunnel (personnel, equipment, and material).
- Contractor staging area outside of tunnel.
- Work trains for rail tunnels; portable platforms for highway tunnels.
- Protection services for contractors (i.e., flagging); safety training for employees.

Countermeasure 39: Interior Roof Concrete Panels

Interior roof concrete panels are appropriate only for flat-topped, cut-and-cover tunnels. The thickness of the concrete panels will depend on the available clearances, the tunnel construction materials (concrete or brick), the depth of cover

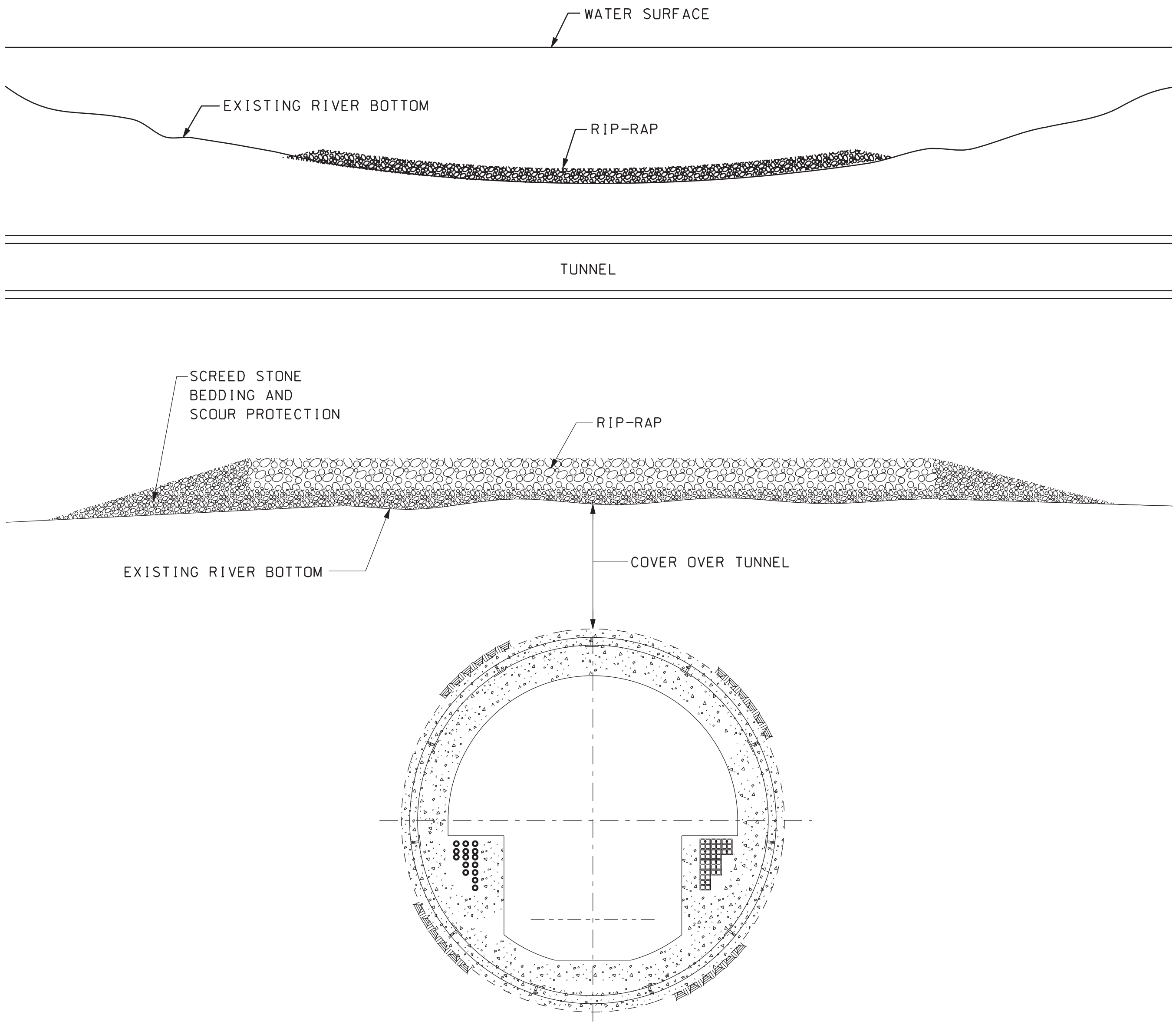


Figure 20. Rip-rap over tunnel.

over the tunnel, the surrounding soil or earth geology, the groundwater conditions, the size of the IED or fire being considered, and the proximity of the hazard or threat to the liner. See Figure 23.

Constructability issues include the following:

- Interior clearances for installation of concrete panels.
- Work hours (weekdays, nighttime, and weekends); required track outages or highway lane closures.
- Limited number of crews per shift due to space constraints.
- Access to tunnel (personnel, equipment, and material).
- Contractor staging area outside of tunnel.
- Work trains for rail tunnels; portable platforms for highway tunnels.
- Protection services for contractors (i.e., flagging); safety training for employees.

Countermeasure 40: Exterior Roof Steel Plates

Exterior roof steel plates are appropriate only for flat-topped, cut-and-cover tunnels. The thickness of the steel plates will depend on the tunnel construction materials (concrete or brick), the depth of cover over the tunnel, the surrounding soil or earth geology, the groundwater conditions, the size of the IED or fire being considered, and the proximity of the hazard or threat to the liner. See Figure 24.

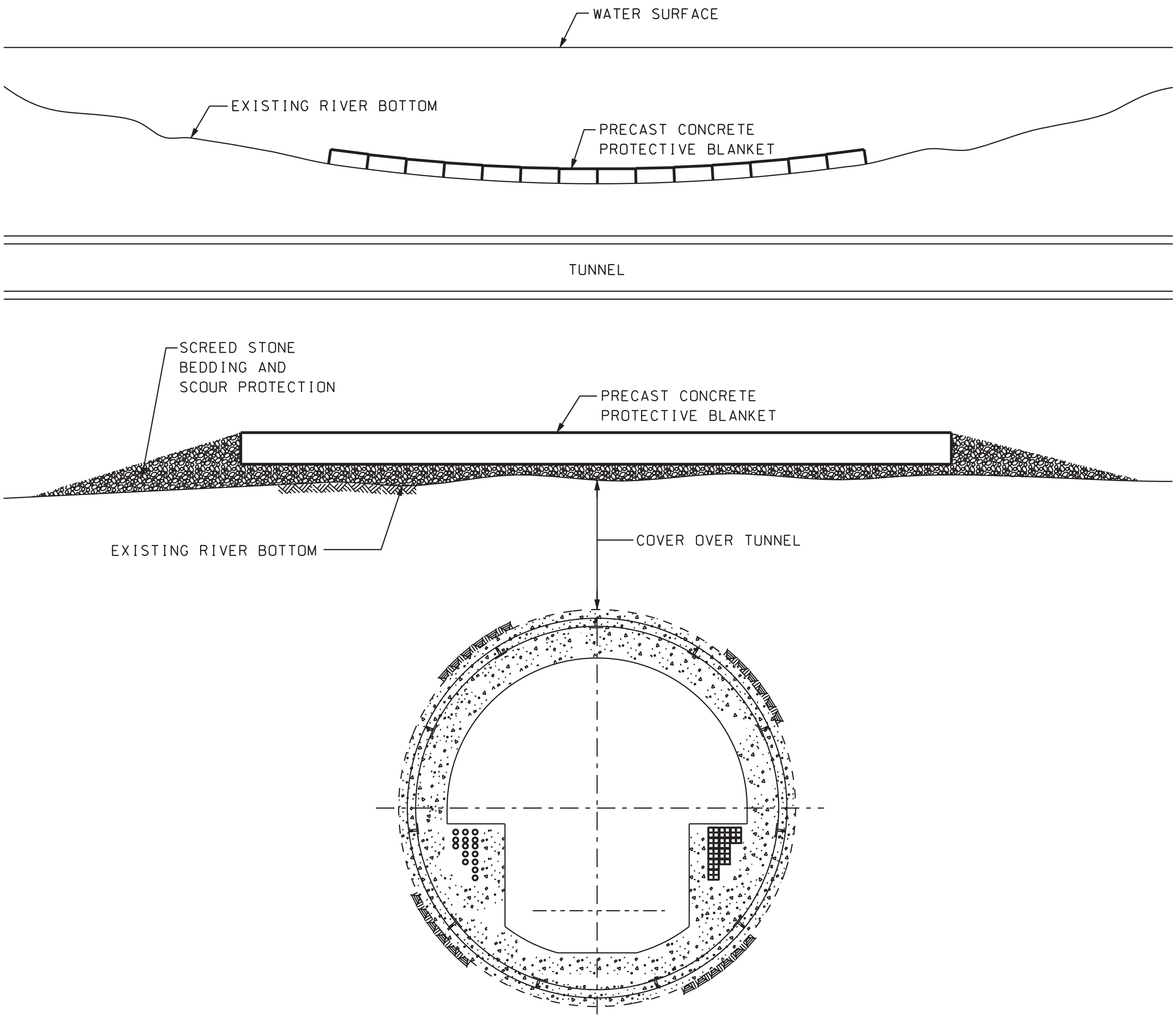


Figure 21. Precast concrete slab over tunnel.

Constructability issues include the following:

- All work is conducted outside of the tunnel.
- Depending on the land use above,
  - Permits may be required,
  - Coordination with other agencies may be required,
  - Utility relocation and coordination may be required, and/or
  - Work hours may depend solely on the contractor's schedule.

Countermeasure 41: Exterior Roof Concrete Panels

The thickness of the concrete panels will depend on the size of the IED being considered and the amount of cover over the tunnel. However, the ground geology and the structural capacity of the tunnel may limit the amount of weight that can be added and, thus, must be taken into consideration. See Figure 25.

Constructability issues include the following:

- All work is conducted outside of the tunnel.
- Depending on the land use above,
  - Permits may be required,
  - Coordination with other agencies may be required,
  - Utility relocation and coordination may be required, and/or
  - Work hours may depend solely on the contractor's schedule.

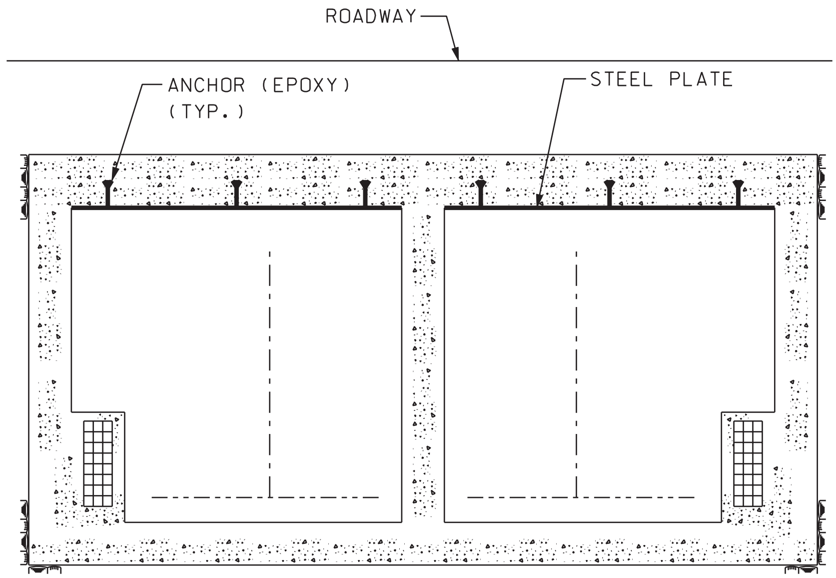


Figure 22. Interior roof steel plates.

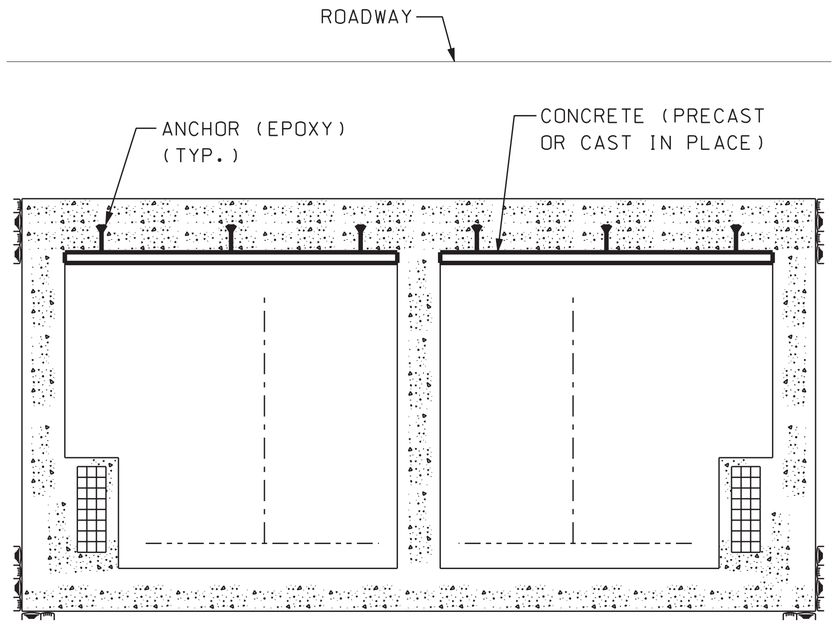


Figure 23. Interior roof concrete panels.

Countermeasure 42: Bollards to Control Access

Bollards are typically constructed around the outside perimeter or across the front entrances of stations or buildings in order to protect the buildings and occupants from vehicles, including those that may be carrying IEDs. The bollards are designed to withstand the force of a speeding van or truck. Depending on the application, bollards can be permanent or removable. See Figure 26.

Constructability issues include the following:

- There must be sufficient property (width and depth) to accommodate the bollards.
- Depending on who owns the property,
  - Permits may be required,
  - Coordination with other agencies may be required,
  - Utility relocation and coordination may be required, and/or
  - Work hours may depend solely on the contractor's schedule.

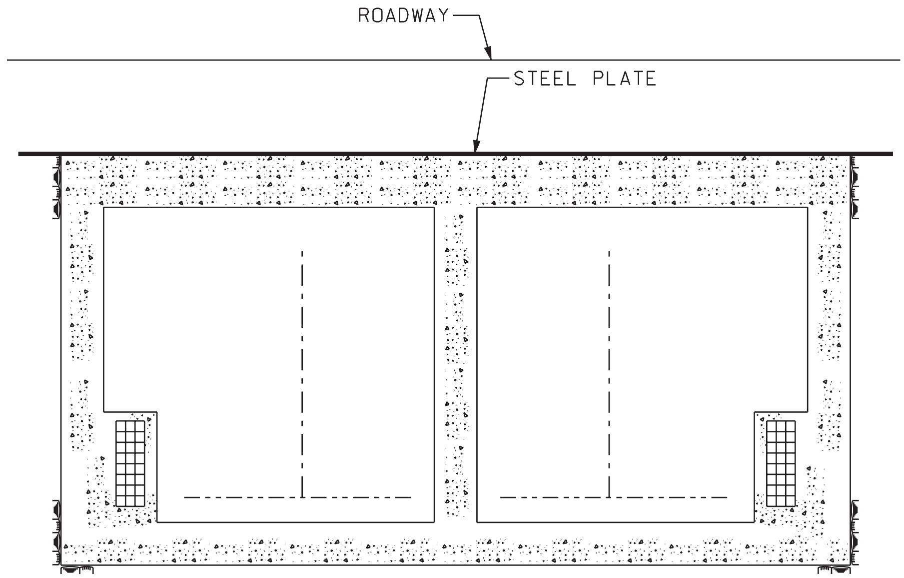


Figure 24. Exterior roof steel plates.

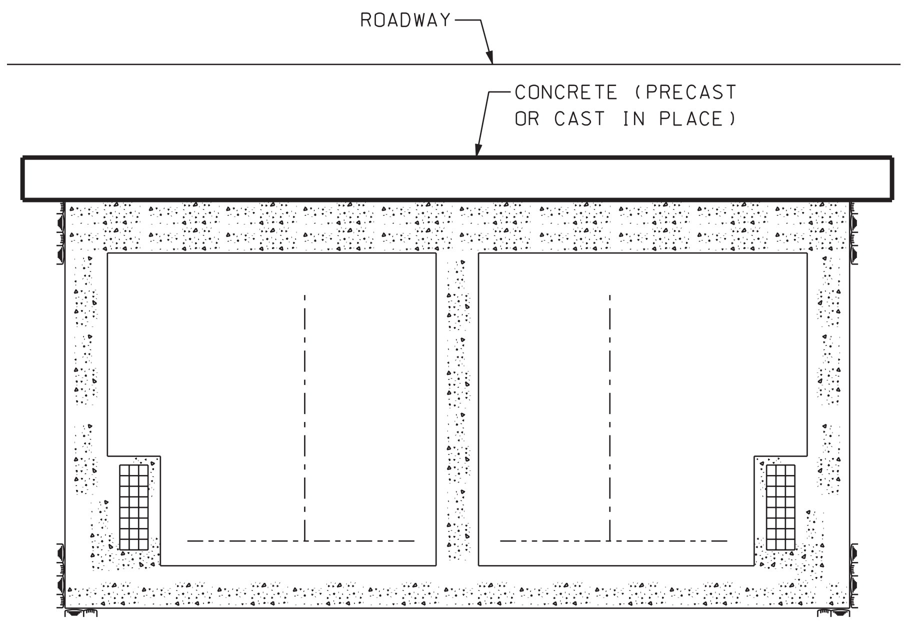


Figure 25. Exterior roof concrete panels.

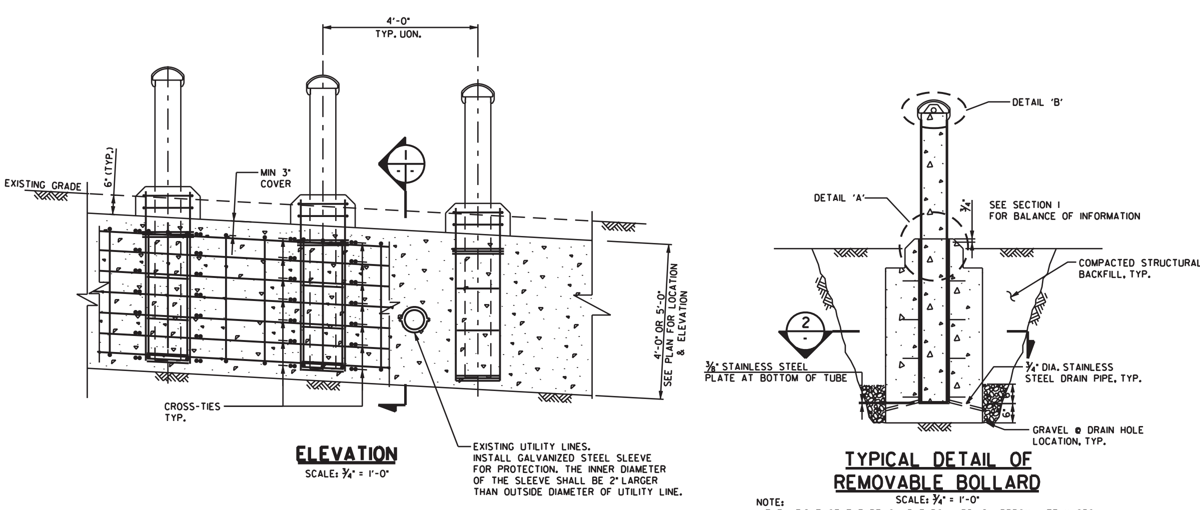


Figure 26. Bollards to control access.

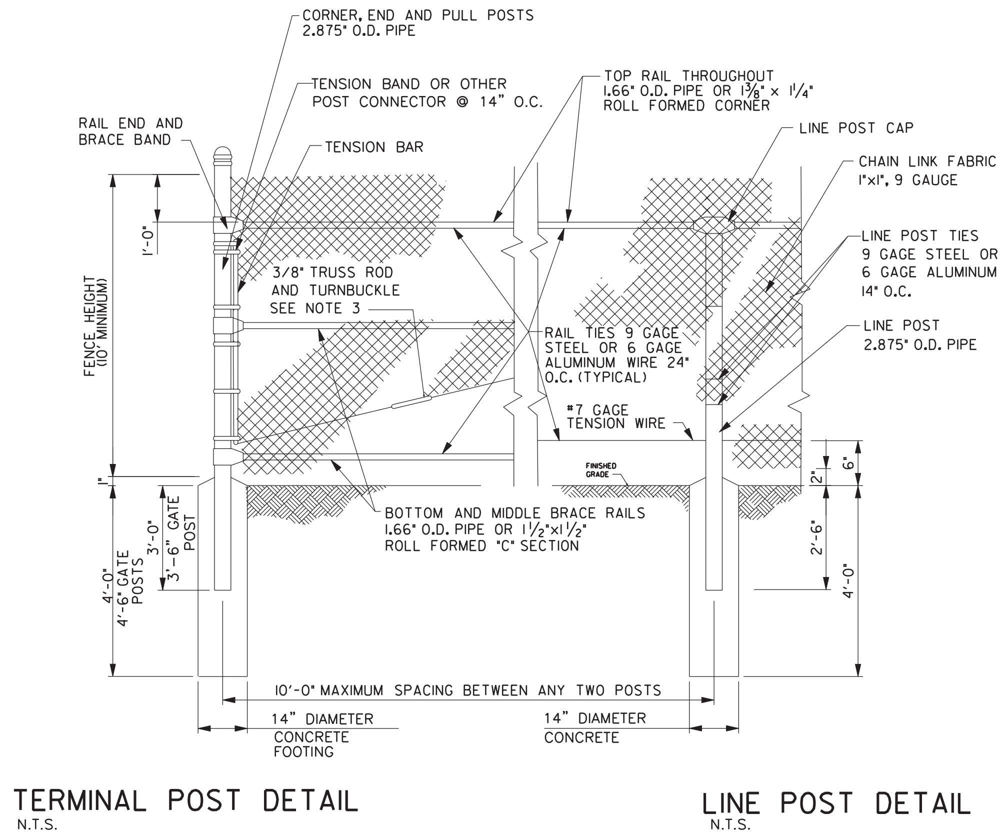


Figure 27. Fencing to control access.

Countermeasure 43: Fencing to Control Access

Fencing is built around the perimeter of a building or facility to keep intruders from entering. There are many different types of fencing. See Figure 27.

Constructability issues include the following:

- There must be sufficient property to accommodate the fencing.
- Depending on who owns the property,
  - Permits may be required,
  - Coordination with other agencies may be required,
  - Utility relocation and coordination may be required, and/or
  - Work hours may depend solely on the contractor's schedule.

Countermeasure 44: Concrete Encasement of Columns

Existing support columns can be strengthened by adding concrete encasements around the steel. This measure can be done for all columns or selected columns. The thickness of the encasement will depend on the size of the IED or fire being considered and the relative proximity of the hazard or threat to the columns. The concrete increases the fire resistance of the column. If additional fire resistance is desired, the concrete can be mixed with polypropylene fibers. See Figure 28.

Constructability issues include the following:

- Interior clearances for installation of concrete encasement.
- Coordination of passengers or other users if area is occupied.

Countermeasure 45: RFP Wrapping of Columns

Reinforced fiber protection (RFP) systems are used for blast hardening and mitigation for circular reinforced concrete columns that support stations and air-rights structures. The RFP wrapping provides strength and ductility to minimize damage; prevent collapse; and enhance blast performance of columns, beams, walls, and ceiling slabs. If fire

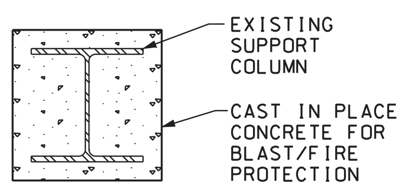


Figure 28. Concrete encasement of columns.

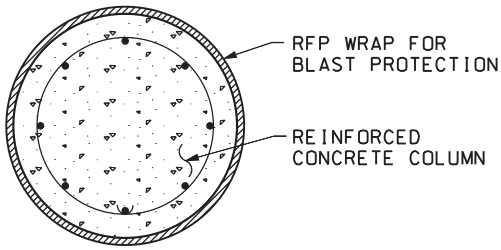


Figure 29. RFP wrapping of columns.

resistance is an issue, there are composite systems on the market that allow the addition of a spray-applied coating on top of the RFP system to increase the fire rating. See Figure 29.

Constructability issues include the following:

- Minor interior clearances for installation of RFP wrapping.
- Coordination of passengers or other users if area is occupied.

Countermeasure 46: Steel Jacketing of Columns

Steel jackets can be installed around existing support columns. The steel jacket can be designed based on the size of the IED or fire being considered and on the relative proximity of the hazard or threat to the columns. See Figure 30.

Constructability issues include the following:

- Minor interior clearances for installation of steel jackets.
- Coordination of passengers or other users if area is occupied.

Countermeasure 47: Redundant Columns or Walls

In some cases, such as a particularly vulnerable air-rights structure or transit station, it may be deemed necessary to build additional support columns or walls. This measure would, of course, increase the support capacity in the event of an explosive or large fire. To justify this level of effort, the hazard or threat scenarios should be examined closely to determine the size of the IED or fire to be considered as well as the proximity of the hazard or threat to the existing and new columns and walls. See Figure 31.

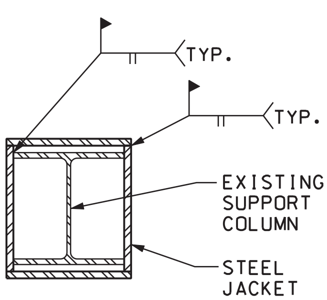


Figure 30. Steel jacketing of columns.

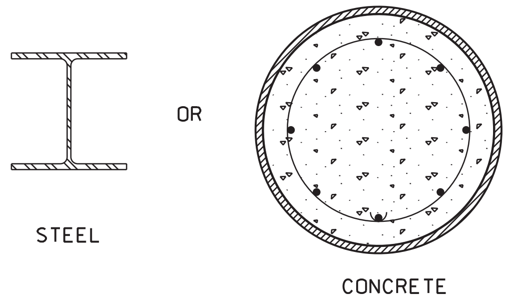


Figure 31. Redundant columns or walls.

Constructability issues include the following:

- The facility must have sufficient space to accommodate the additional columns and/or walls.
- Applicable fire and life-safety (i.e., egress) codes must be considered if new walls are constructed.
- Coordination of passengers or other users if area is occupied.

Countermeasure 48: Floodgates

Flooding in a tunnel can be extremely dangerous and damaging. This is particularly true if an underwater tunnel is interconnected with other tunnels and/or passenger stations because the water has the potential to travel farther, cause more destruction, and interrupt tunnel operations. To lessen the potential for extensive flooding from situations such as these, floodgates are sometimes installed. See Figure 32.

Constructability issues include the following:

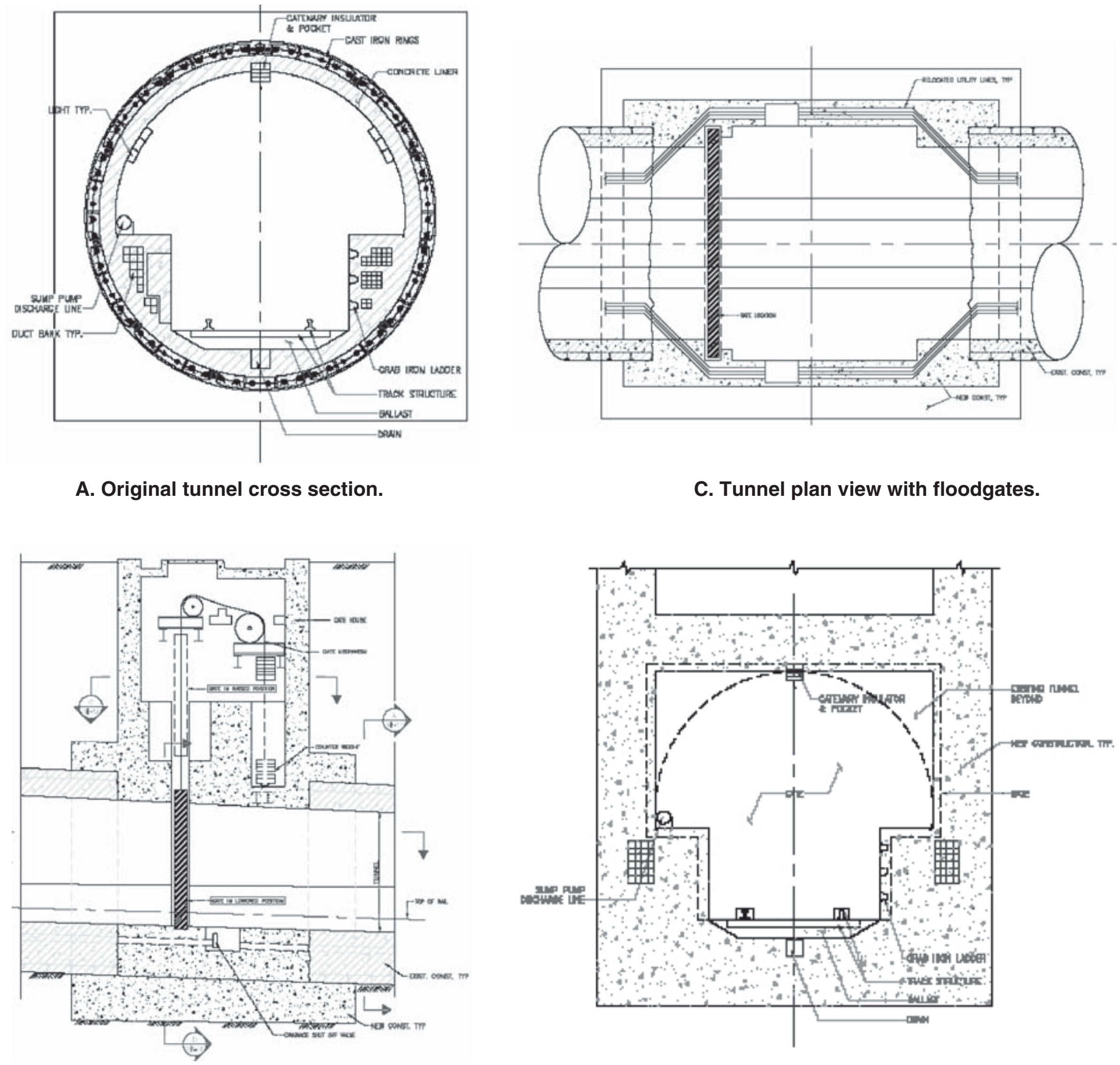
- Significant vertical clearances for installation of floodgates.
- Extensive tunnel utility relocation.
- Work hours (weekdays, nighttime, and weekends); required track outages or highway lane closures.
- Limited number of crews per shift due to space constraints.
- Access to tunnel (personnel, equipment, and material).
- Contractor staging area outside of tunnel.
- Work trains or portable platforms; protection services for contractors (i.e., flagging); safety training for employees.

Countermeasure 49: Barrier Walls

Barrier walls are sometimes constructed on the water side of a tunnel portal to create a stand-off distance and protect the portal from waterborne hazards and threats, such as off-course ships or ships carrying explosives. See Figure 33.

Constructability issues include the following:

- Environmental issues require permits and approval from responsible agencies.
- Coordination with water traffic authorities.



A. Original tunnel cross section.

C. Tunnel plan view with floodgates.

B. Tunnel elevation with floodgates.

D. Tunnel cross section with floodgates.

Figure 32. Floodgates

- Contractor staging area outside of tunnel.
- Underwater construction expertise required.

Countermeasure 50: Bollards or Fenders in the Water

Bollards or fenders can be constructed on the water side of a tunnel portal to create a stand-off distance and protect the portal from waterborne hazards and threats, such as off-course ships or ships carrying explosives. See Figure 34.

Constructability issues include the following:

- Environmental issues require permits and approval from responsible agencies.
- Coordination with water traffic authorities.
- Contractor staging area is outside of tunnel.
- Underwater construction expertise required.

5.5 Conclusion

When using these guidelines, one must recognize that most mitigation countermeasures fall between two extremes. One extreme is to prevent all damage at enormous cost, and the other extreme is to spend nothing and risk enormous damage. Tunnel owners, operators, and engineers must make balanced decisions in selecting countermeasures for their facilities, preferably to risk an acceptable level of damage at a reasonable cost. However, finding this balance becomes more complicated when considering possible loss of human life, which is extremely difficult

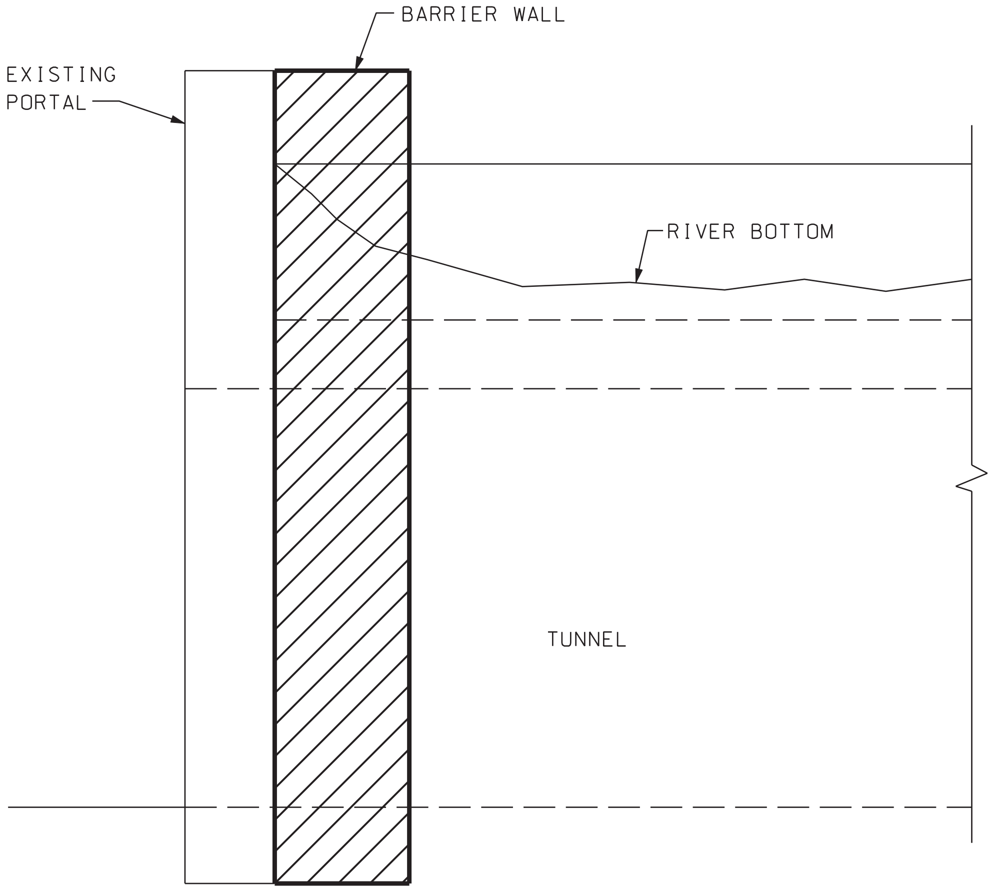


Figure 33. Barrier walls.

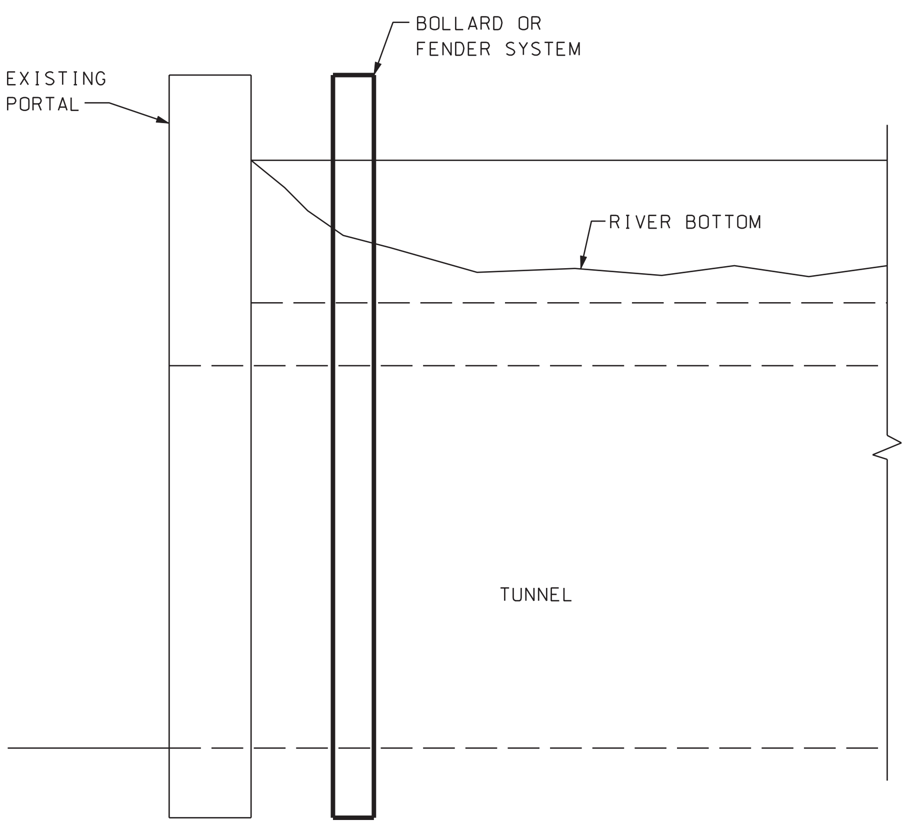


Figure 34. Bollards or fenders in the water.

if not impossible to assign a value to. Protection of human life should always receive the highest priority.

While preparing budgets for tunnel-hardening countermeasures, be careful to include the costs associated with labor, material, equipment, protective services (i.e. flagging), outage costs of highways or rail lines, and interruption of traffic and operations during construction. Although the relative effectiveness and order-of-magnitude cost ratings in the countermeasure guides are based on many years of engineering expertise and past project experience, the rating systems are subjective. They depend on a number of variables, including tunnel length, tunnel construction type, construction materials, surrounding earth geology and groundwater conditions, available clearances, and interruption of operations. To further explore the suitability of particular countermeasures to a specific facility, in-house or outside experts should be used to develop conceptual designs and cost estimates. Once these designs and estimates meet approval, final construction documents—including design drawings, specifications, construction cost estimates, and schedules—should be developed.

CHAPTER 6

System Integration

6.1 Introduction

The seemingly disparate safety and security countermeasures identified in Chapter 5 may be incorporated into an integrated system. This approach uses a system methodology to improve tunnel safety and security.

6.2 System Safety and Security

System safety and security is the systematic application of engineering, technology, and management tools to identify, analyze, and control hazards and threats within operational, budget, and time constraints. It encompasses all of the integral factors that make up a tunnel system:

- People—tunnel operating and maintenance personnel, the public, emergency responders, and vendors.
- Operating procedures—routine operating procedures, emergency procedures due to a security or safety incident, and measures implemented due to a particular hazard or threat.
- Engineering and technology systems and controls—communication systems, ventilation systems, intrusion detectors, lighting, fencing, and so forth.
- Physical aspects of the tunnel structure.

Each of these elements, independently, provides some degree of safety and security. However, when combined, they significantly improve safety and security. Tunnel operation and maintenance personnel, for example, can be trained to recognize and report suspicious behavior in and around a transportation tunnel. Fences and barriers define areas where unauthorized personnel are not permitted. Lighting aids in the observation of activity. When these disparate systems are integrated, the likelihood of deterring and detecting a security incident is greatly increased. An effective safety and security system can be developed when one understands the interrelationships of these systems and integrates them so that they operate as a whole.

6.2.1 People

Tunnel Personnel

Training of tunnel operation and maintenance personnel is an important and integral component of ensuring tunnel safety and security. Tunnel personnel can be a key element to deterring, detecting, and responding to a safety or security incident. Tunnel personnel should be trained to recognize suspicious packages, activity, and behavior and to react accordingly. They must also be taught how to respond to an actual safety or security incident. In order to carry out these responsibilities, tunnel personnel must have a basic understanding of their role as the eyes and ears of tunnel operations and of their responsibility for safety and security. They should be trained to recognize things that are out of the ordinary and to identify suspicious actions that might constitute pre-attack activity. In particular, their instruction should include the difference between unattended packages and suspicious packages, as well as what constitutes a suspicious security event. When all unattended packages and unwarranted activity are deemed "suspicious," unnecessary disruption of the tunnel system occurs. Tunnel personnel should also have a clear understanding of the proper procedures for reporting and responding to an event.

Specific technical training should be afforded to central control personnel or others who are responsible for activating emergency systems, such as ventilation and fire suppression systems (i.e., dry standpipes), or de-energizing traction power systems in rail transportation tunnels.

Lastly, tunnel personnel training should include coordination with the many agencies and departments that may be necessary during the management of a tunnel security incident, such as police, fire and rescue departments, emergency medical services, and other forms of technical assistance. This training should include the following:

- An overview of the incident command system (ICS),
- Coordination with emergency responders, and
- Evacuation protocols.

Emergency Responders

Tunnels can be viewed as inherently hazardous. Vehicular and train traffic, traction power in rail tunnels, and the confined nature of the space all challenge and impact emergency response capability. Tunnel operators should develop formal training programs for emergency responders. The training should consist of the following:

- Inherent hazards—vehicular traffic, rail traffic, and traction power (rail systems only).
- Right-of-way safety.
- Tunnel life safety systems—ventilation, fire detection, fire suppression and hydrants, points of egress, and rescue areas.
- Communication systems—capabilities and limitations and emergency telephone locations.
- Training aids—checklists, facility diagrams, and so forth.

The Public

The public can play an important role in reporting suspicious packages and activities. A public security awareness campaign can be designed to heighten the security awareness of the public. The public should be encouraged to be aware of their surroundings and to look for suspicious or unusual activity. The campaign should emphasize the following:

- What to look for,
- How to report the information and
- What tunnel emergency elements are available (exits, evacuation procedures, fire extinguisher locations, emergency telephone locations, and so forth).

The FTA's Transit Watch program is an example of a public security outreach program.

6.2.2 Operating Procedures

An effective response to any safety or security incident includes predetermined response procedures for both tunnel operators and emergency response personnel. The foundation for the procedures is an emergency plan that establishes the policies and guidelines for the procedures. The procedures are typically jointly developed by tunnel operation departments, tunnel safety/security departments, and emergency responders (including fire and police). These procedures serve as guidance during the response to a safety or security incident and include specific actions that are to take place by tunnel operation and maintenance personnel, central control staff, and other tunnel staff. The procedures should include the following:

- Reporting protocol;
- Facts to be collected and evaluated;
- Verification protocol;
- Protection of the scene;
- Limiting vehicular and train traffic;
- Right-of-way safety;
- Vehicle safety (transit, rail vehicles, and special vehicles);
- Removal and restoration of traction power;
- Activation of emergency systems, including ventilation and dry standpipe system;
- Assistance in rescue and evacuation operations;
- Deployment of roving patrols;
- Posting of guards;
- Hazardous materials restrictions;
- Background investigations of employees and vendors;
- Inspections of vehicles, cargo, and persons;
- Bomb-sniffing dogs;
- Credentialing; and
- Command protocol.

The cornerstone of the procedures is the sharing of information and responsibilities between emergency responders (fire, law enforcement, and emergency medical services) and the tunnel owners and operators. When designing programs to respond to safety and security incidents, understanding the activities to be performed is essential. These activities must take place in advance of developing specific response protocol.

An interorganizational memorandum of understanding or agreement (MOU or MOA) is the basis for acknowledging what resources each organization will provide during a response.

6.2.3 Engineering and Technological Systems and Controls

Engineering Systems and Controls

Fire protection, fire detection, ventilation systems, lighting, fencing, and barriers are among the engineering controls that support tunnel safety and security. These measures provide access control for deterring an attack, assist in the detection of intruders, and limit the damage potential of an incident due to fire or toxic gases and substances.

Technological Systems and Controls

Technology systems and controls encompass a wide range of measures, including, but not limited to, access control systems (identification card readers, intrusion detection systems, CCTV, communication systems, and C/B/R detectors). Each of the systems should be evaluated to determine what is suitable for the particular application. In order to make this determination, it will be necessary to know the operational aspects of the security system and how the security system will be used. Consequently, successful deployment of a technology requires the development of a needs assessment, desired performance characteristics, and training of staff to operate and maintain the technology. The technology will be based on the hazard or threat assessment. Study of the technologies currently available determines current capabilities.

Table 72 illustrates how the various countermeasures deter, detect, and respond to a hazard or threat.

6.2.4 Physical Aspects of the Tunnel Structure

Physical aspects of the tunnel structure include length, cross section, portal locations, cross-passage locations, and other points of access. Physical hardening of the tunnel structure minimizes the damage potential of a hazard or threat and helps to maintain the structural integrity. See Section 5.4 for more detailed information.

6.3 Security System Integration

Integrated security measures can deter a potential security incident by making it more difficult to execute, increase the likelihood of detection, minimize the damage potential of an incident, and aid in response and recovery efforts. As an example, the use of intrusion technology can assist in both the deterrence and detection of an intruder, thereby perhaps preventing a terrorist attack or simply the destruction or vandalism of property. Roving patrols and guards coupled with a detection system can be used to monitor unauthorized access into a tunnel and its associated facilities.

An integrated security system design must take into consideration the physical aspects of the operating environment, the performance capability of the systems, and the personnel requirements for operation and maintenance. As previously discussed, an integrated security system consists of

- People,
- Operating procedures,
- Engineering and technology systems and controls, and
- Physical aspects of the tunnel structure.

Table 72. How countermeasures deter, detect, and respond to hazards and threats.

Deterrence	Detection	Response
• Operational Tactics – Roving patrols – Bomb-sniffing dogs – Background checks of employees and contractors – Background checks of facility vendors – Access control – Credentialing and identification card system – Guards at entry points – Intelligence – Hazardous material restriction – Inspections • Technology – CCTV – Intrusion detectors – System integration • Engineering – Blast design – Elimination of hidden corners, alcoves, and shelves – Open, unimpeded lines of sight – Lighting – Locked facility doors	• Operational Tactics – Intelligence – Security awareness training of operating and maintenance personnel – Roving patrols – Guards at entry points – Bombing-sniffing dogs – Identification card system – Inspections • Technology – Intrusion detectors – Identification card readers – Chemical/biological/radiological detectors – Seismic/stress detectors – Mobile monitoring – Explosive detectors – System integration • Engineering – Fire detection	• Operational Tactics – Command and control (multi-tenant) – Evacuation protocol – Information sharing – Tunnel ventilation – Portable fire extinguishers • Technology – CCTV system – Communication – Chemical/biological/radiological monitoring – Explosive detectors – Interface with traffic monitoring – System integration • Engineering – Fire protection – Lighting – Ventilation

Before a system can be integrated, adequate resources should be allocated to planning, defining the system requirements, and implementing the design stages of the project. An assessment must be carried out to determine the capability of the existing system, the present requirements, and possible future requirements. Some of the major considerations are as follows:

- **System codes and standards—**Appropriate standards should be used to ensure that each of the systems is capable of being assembled into an integrated system. These standards should address system components, including communication protocols, communication interfaces, data dictionaries, and message sets.

  Designing to standards such as Synchronous Optical Network (SONET), Asynchronous Transfer Mode (ATM), and Ethernet allows operability between manufacturers. Future system requirements are always difficult to predict, and an upgrade path for computer and communication systems should always be available. For instance, in order to accommodate future upgrades as improved technology becomes available, one may specify standard rack-mounted and blade servers as well as a SONET platform, which is scaleable from OC 48 to OC 192 by upgrade of the optics. Other applicable standards are available from the Electronics Industries Association (EIA), the International Electrotechnical Commission (IEC), the American National Standards Institute (ANSI), the Institute of Electrical and Electronics Engineers (IEEE), and others.

  Individual code requirements should also be assessed. For example, integration of a fire alarm system must take into account the requirements of *NFPA 72: National Fire Alarm Code*, as well as the requirements of *UL Standard 827: Standard for Safety for Central-Station Alarm Services*.
- **Device compatibility—**A primary decision in the design phase is determining which interfaces need to communicate with each other and whether these interfaces are human or electronic. Interoperability of the security devices needs to be considered to ensure functional compatibility.

  An integrated system has many advantages, including a common operator interface for individual MEC systems, common alarms, and a real-time database. An integrated system offers the flexibility to view and control the individual systems from different locations and to export data to external agencies. However, integrating systems is expensive, especially for older systems. Therefore, before integration is undertaken, one should carefully evaluate the potential cost of integration as well as budget limitations.
- **Data communication—**Data communication must be considered when integrating different systems.

  A typical system upgrade might accommodate a planned increase in communication bandwidth and data requirements along with a phased migration of MEC systems to the integrated system. For instance, allowances might be made for the future integration of a new digital CCTV system.

  Assessment must be an ongoing exercise. For example, if voice-over IP (VoIP) communications are to be added to an Ethernet local area network (LAN), then an assessment should be made to determine if the response time of an emergency system on the same LAN is still acceptable.

  Traditional safety-related systems have well-defined safety boundaries that can be assessed for availability and integrity. When a system is integrated, the influence of other MEC systems can blur the safety boundaries and degrade the safety system. It is important to ensure that this does not happen. The damage potential of the integrated system failing should also be assessed for each case. As an example, a tunnel ventilation system does not usually have a default fail-safe running condition, and a supervisory command must be received to set the mode of operation (i.e., supply or exhaust) to properly drive the smoke and heat away from escaping passengers.
- **Integrated legacy systems—**When introducing new technologies into an existing system, compatibility must be considered. If possible, consideration should be given to introducing an interface rather than changing the existing architecture.

  When interfacing to a legacy (i.e., existing) communication system, the hardware interface is typically relatively straightforward. The more complicated issue tends to be the software. If a software driver is not available for the system writing, a new driver for the communication protocol can range from trivial to extremely difficult and expensive. It is very important for the owner or operator to give guidance on how to accurately specify this work so that a system integrator can assess the degree of difficulty before bidding the job. There are also costs associated with maintenance and support of the third-party communication software.

The following are typical steps for developing an integration strategy:

1. Identify proposed locations for the operational control center and backup secondary control center. Size requirements can be considered after the system assessment is carried out.
2. Establish a communication backbone, taking into consideration
   - Bandwidth requirements (this is covered in more detail below);
   - Technology choices (i.e., SONET, ATM, and Ethernet); and
   - Physical structure, redundancy, and diverse routing of fiber links.

3. For each individual system, identify performance criteria, functionality requirements, code requirements, and level of security (safety-critical, safety-related, and so forth). Also identify fall-back requirements.
4. Determine whether or not each individual system can be integrated. For example, the video channels to be taken back to the control center and the real-time performance requirements will determine the bandwidth of a CCTV system. It must be determined if this bandwidth can be accommodated on the communication backbone.
5. Determine the level of integration that can be achieved within the budget.
6. Assess the worst case (i.e., maximum) bandwidth that includes all possible commands necessary during an incident (equipment control, multiple alarms, traffic monitoring and control, frequent VoIP communications, and so forth).
7. Evaluate the computer architecture, including the following:
   - Client server,
   - Peer-to-peer architecture,
   - Redundancy issues,
   - Expansion capability,
   - Real-time performance, and
   - Database requirements.
8. Choose an off-the-shelf or custom-made supervisory control and data acquisition (SCADA) software design based on the desired performance level and budget.
9. For each system, determine system integration options, levels of interoperability, and whether migration paths can be achieved with the integrated system.
10. Conduct a phased replacement program of the obsolete systems.
11. Design the operations control center theater, including desks and the video wall.
12. Determine the power supply requirements, including the uninterrupted power supply with backup generators.
13. Ensure that devices are hardened or concealed to guard against tampering and vandalism. Network access and data communications should be secured by firewalls, password protection, encryption, and authentication.
14. Perform testing and simulation to ensure the functionality of the system.

6.4 Information Sharing

The aforementioned guidelines are particularly critical for transportation tunnels. Because it is not uncommon for transportation tunnels to cross municipal or governmental boundaries, these tunnels may have multiple users or tenants. Response to an emergency incident typically requires close coordination among the multiple users, including law enforcement, fire departments, and emergency medical services from the responding jurisdictions. The tunnel operating authority or agency has the primary responsibility for emergency management planning and initiation of an immediate response to incidents. However, a coordinated response among all entities involved is critical to minimizing the damage potential of the incident or event. It stands to reason that integration of tunnel systems, such as CCTV systems, is warranted. It is desirable to track suspects or events that move from one jurisdictional boundary to another within the tunnel environment. Without a coordinated and integrated system, such tracking is not possible.

Tunnel tenants and users should have emergency response plans for their respective operations that address emergency response coordination. The tunnel owners and operators must ensure that all stakeholders—including tenants; emergency response agencies at the local, state, and federal levels; and municipal or governmental jurisdictions, as appropriate—are actively involved in the development of an all-hazards emergency response plan that outlines roles and responsibilities, coordinates efforts, and integrates each tenant user.

6.5 Conclusions

System safety and security are the systematic application of engineering, technology, and management tools to identify, analyze, and control hazards and threats within operational, budget, and time constraints. Systems encompass all of the integral factors that make up a tunnel, including people, operating procedures, engineering and technology systems and controls, and the physical aspects of the tunnel structure. Each of these elements independently provides some degree of safety and security. However, when combined, they significantly improve safety and security.

CHAPTER 7

Future Research

Many potential research items have been identified throughout the research. These items, in order of priority, are as follows:

1. Develop a pocket-sized user guide.
2. Develop a CD containing the report tables.
3. Collaborate with European research programs.
4. Evaluate the effects of fire on the tunnel structure.
5. Evaluate the effectiveness of current tunnel fire detection systems.
6. Summarize and publish a set of "lessons learned."
7. Develop a best practices manual.
8. Identify changes in operation protocols to enhance safety.
9. Develop a set of sample emergency response procedures.
10. Develop a program to conduct a series of interactive owner orientation workshops.
11. Develop more effective broad-based fire detection systems.
12. Develop ground improvement retrofitting schemes.
13. Develop guidelines for vehicle inspections.
14. Develop design criteria for new tunnels.
15. Develop a program to encourage development of more effective fire detection systems.
16. Develop a program to conduct interactive industry feedback workshops.
17. Develop an interactive electronic version of this report.
18. Evaluate the effectiveness of current tunnel fire suppression systems.
19. Identify retrofit technologies to enhance safety.
20. Develop a program to encourage development of more effective fire suppression systems.
21. Develop a tunnel-specific inspection manual.
22. Develop advanced coordinated control schemes for ventilation systems.
23. Build test tunnels or models.
24. Conduct structural blast damage potential analyses.
25. Develop intelligent egress systems.
26. Research issues identified by case studies.

Table 73 shows these research items and the estimated schedule and cost associated with each item.

The criteria employed to determine the above prioritization are as follows:

- The resultant impact on the potential safety and security of transportation tunnels,
- The estimated duration of the effort involved to secure results, and
- The estimated cost of securing results.

The following sections discuss each potential research item in detail.

7.1 Pocket-Sized User Guide

A user guide that contains critical documents of this report (Tables 14 through 16 and 25 through 41) could be produced. This user guide would be available for tunnel owners, operators, and engineers as a pocket-sized manual for easy use.

7.2 Report Tables on a CD

A CD containing the report tables could be produced to facilitate the goal of making the tables easier to use. Although this effort would not achieve the same level of automation as the interactive database described in Section 7.17, it would consolidate the tabular information contained herein. This would make most sense for the structural and system vulnerability tables (Tables 14 through 16 and 25 through 27, respectively), the structural and system hazard and threat directories (Tables 28 through 30 and 31 through 33, respectively), the countermeasure guides (Tables 34 through 41), and the countermeasure descriptions sheets (Sections 5.4.1 through 5.4.3). Rather than sifting through many sheets of paper, the user would be able to conduct searches within the

Table 73. Future potential research issues.

Priority Rank	Future Potential Research	Text Section	Estimated Schedule (months)	Estimated Cost ($1,000)	Remarks
1	Develop a pocket-sized user guide	7.1	3	35	
2	Develop a CD containing the report tables	7.2	6	60	
3	Collaborate with European research programs	7.3	6	60	
4	Evaluate the effects of fire on the tunnel structure	7.4	6	60	
5	Evaluate the effectiveness of current tunnel fire detection systems	7.5	12	200	Current research by NFPA
6	Summarize and publish a set of "lessons learned"	7.6	6	60	
7	Develop a best practices manual	7.7	12	120	
8	Identify changes in operation protocols to enhance safety	7.8	12	120	
9	Develop a set of sample emergency response procedures	7.9	12	120	
10	Develop a program to conduct a series of interactive owner orientation workshops	7.10	6	120	
11	Develop more effective broad-based fire detection systems	7.11	24	200	Work being done by national labs
12	Develop ground improvement retrofitting schemes	7.12	12	150	
13	Develop guidelines for vehicle inspections	7.13	9	90	
14	Develop design criteria for new tunnels	7.14	12	160	
15	Develop a program to encourage development of more effective fire detection systems	7.15	12	120	
16	Develop a program to conduct interactive industry feedback workshops	7.16	6	60	
17	Develop an interactive electronic version of this report	7.17	18	360	
18	Evaluate the effectiveness of current tunnel fire suppression systems	7.18	18	200	
19	Identify retrofit technologies to enhance safety	7.19	6	60	
20	Develop a program to encourage development of more effective fire suppression systems	7.20	12	120	
21	Develop a tunnel-specific inspection manual	7.21	12	120	
22	Develop advanced coordinated control schemes for ventilation systems	7.22	12	120	
23	Build test tunnels or models	7.23	48	2,000+	
24	Conduct structural blast damage potential analyses	7.24	12	200	
25	Develop intelligent egress systems	7.25	24	400	
26	Research issues identified by case studies	7.26	0	0	See Rank Item #6

electronic files to narrow down and identify the possible countermeasures for his or her facility.

7.3 Collaboration with European Research Programs

U.S. researchers could collaborate with new European research programs to stretch the dollars that are available for tunnel safety research. Eight particularly promising research projects were launched by the European Union after the serious road tunnel fires beginning with the Mont Blanc Tunnel fire in 1999: Durable and Reliable Tunnel Structures (DARTS); Fire in Tunnels (FIT); Cost-effective, Sustainable and Innovative Upgrading Methods for Fire Safety in Existing TUNnels (UPTUN); SafeTunel; VirtualFires; Safe-T; Sirtaki; and L-Surf. Several of these projects have been completed, and the remainder will conclude shortly.

To keep the drive and the unique accumulation of scientific and pragmatic potential of their consortia, as well as to foster networking activities worldwide, the eight projects have proposed to launch a Committee on Operational Safety of Underground Facilities (COSUF). This committee will be under the umbrella of the ITA, in close cooperation with the PIARC.

7.4 Effects of Fire on the Tunnel Structure

The document entitled, "Guidelines for Structural Fire Resistance for Road Tunnels" [Ref. 21], published by ITA and jointly prepared by ITA and PIARC, addresses the impact of fire on road tunnel structures. Similar research could address the impact of fire on transit and rail tunnel structures.

7.5 Effectiveness of Current Tunnel Fire Detection Systems

Researchers could assess the effectiveness of the myriad fire detection systems that are currently available for tunnel applications, including linear detectors, spot detectors, visibility-measuring devices, radiation heat detectors, gas detectors, and video detectors.

Currently, the NFPA Research Foundation, in conjunction with the National Research Council of Canada (NRCC), is conducting a research project that addresses the effectiveness of current fire detection systems in road tunnels [Ref. 22]. Ten detection systems will be tested, including linear detectors, CCTV (flame and smoke) detectors, flame detectors, and spot detectors. Tests will be conducted in both a test tunnel and an active functioning tunnel. This project might pose an opportunity to cosponsor research with the NFPA and the NRCC.

7.6 Summary of Lessons Learned

Lessons learned from the case studies in Chapter 3 could be published, along with the further research described in this chapter. This document would be a learning tool for all transportation tunnel owners and operators.

7.7 Best Practices Manual

A best practices manual for road tunnels has been developed by PIARC and was published in 2005 [Ref. 23]. It addresses quality, safety and risk management, maintenance and operation, training and emergency exercises, renovation of tunnels, risk evaluation tools, and financial decision-making tools. Using the results of this report, similar research could develop a best practices manual for transit and rail tunnels.

7.8 Changes in Operation Protocols to Enhance Safety

Operation protocols currently being employed by existing transportation tunnel agencies could be reviewed, along with the protocols proposed by various standards and guidelines. A list of changes or improvements to the existing operation protocols that would enhance the safety and security of the country's transportation tunnels could be developed.

7.9 Sample Emergency Response Procedures

Using recommendations promulgated by organizations such as the NFPA and PIARC, a set of sample emergency response procedures could be developed that would address all potential emergencies. Using this set of sample emergency response procedures, a tunnel owner or operator would be able to create a facility-specific set of emergency response procedures, including an emergency response plan (ERP).

7.10 Owner Orientation Workshops

A program to conduct a series of interactive owner orientation workshops could be developed at a national (but not international) level, such as the meetings conducted by AASHTO, the International Bridge, Tunnel and Turnpike Association (IBTTA), and the ITA. The purpose of these workshops would be to provide tunnel owners and operators with the opportunity to understand the rationale behind this report and the report's potential impacts on their particular tunnels.

A suggested outline for the structure of these workshops is as follows:

1. Introduction
2. Objectives of this document
3. Outline of this document
4. Understanding the underlying concepts
5. Potential hazards and threats
6. Lessons learned from case studies
7. Tunnel vulnerabilities
   – Incident damage potential
   – Vulnerabilities of specific tunnels
8. Application guidelines
9. Interactive examples of application to specific tunnels
10. Conclusions

7.11 More Effective Broad-Based Fire Detection Systems

During a C/B/R incident, any decision regarding the mitigation measures to be taken will depend on the speed and accuracy of the detection system. However, detection systems currently in use in transportation tunnels are only capable of detecting smoke, temperature, and certain tailpipe exhaust constituents. As discussed in Chapter 2, the introduction of C/B/R agents into the tunnel environment has become a very dangerous threat. Therefore, researchers could develop more effective systems that can detect and identify various gases and liquids.

Several national laboratories and manufacturers have been working for some time on developing detection systems that can meet speed and accuracy requirements. In fact, several prototype systems have already been deployed in transit systems and tunnels.

The current status of detection system research and development projects could be gathered and compiled. A program to encourage continued development or to fill in the gaps where research and development efforts are lacking could be developed.

7.12 Ground Improvement Retrofitting Schemes

Retrofitting existing tunnel structures to enhance tunnel resistance to blasting generally requires high and sometimes prohibitive costs, and retrofitting work is often subject to significant constraints from the operational standpoint (e.g., constraints due to clearance requirements or requirements to avoid service disruption). There is, therefore, a significant incentive for developing new retrofitting techniques to address these concerns. Because information on the use of ground improvement technology is currently very limited, researchers could work to expand the knowledge base in this area and to improve ground improvement technology. Results from this research work would greatly benefit future retrofit projects.

7.13 Guidelines for Vehicle Inspections

Vehicle inspection requirements currently being employed at existing facilities could be evaluated in order to develop a general set of guidelines that would permit an owner to create a set of appropriate vehicle inspection requirements for the specific tunnel facility.

7.14 Design Criteria for New Tunnels

Researchers could compile all of the new-tunnel design criteria from various organizations into one reference source. Currently, several organizations must be consulted for industry standards or guidelines for the design of tunnel elements. These organizations include the following:

- For tunnel structural elements:
  – American Concrete Institute (ACI),
  – American Institute of Steel Construction (AISC),
  – American Welding Society (AWS),
  – FHWA,
  – ITA,
  – *Tunnel Engineering Handbook* [Ref. 24],
  – *Civil Engineering Handbook* [Ref. 25], and
  – Others.
- For tunnel system elements:
  – American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE),
  – NFPA,
  – PIARC,
  – *Tunnel Engineering Handbook* [Ref. 24],
  – *Handbook of Tunnel Fire Safety* [Ref. 26],
  – *Fire Protection Handbook* [Ref. 27], and
  – Others.

7.14.1 Tunnel Structural Elements

The ACI provides two important codes: *Building Code Requirements for Structural Concrete* [Ref. 28] and *Code Requirements for Environmental Engineering Concrete Structures* (for durability) [Ref. 29].

The AISC provides the *Steel Construction Manual* [Ref. 30].

The AWS provides the *Structural Welding Code for Steel* [Ref. 31] and *Structuring Welding Code for Reinforcing Steel* [Ref. 32].

7.14.2 Tunnel System Elements

In ASHRAE's handbook, titled *Heating, Ventilation and Air Conditioning (HVAC) Applications*, a chapter (titled "Enclosed Vehicular Facilities") discusses the design of environmental and smoke control systems for all types of transportation tunnels [Ref. 33].

The NFPA provides two standards that address the design of tunnel system elements related to fire protection:

- *NFPA 130: Fixed Guideway Transit and Passenger Rail Systems Standard* [Ref. 2] and
- *NFPA 502: Road Tunnels, Bridges, and Other Limited Access Highways Standard* [Ref. 5].

In addition, the NFPA provides guidelines for the design of the fire protection and emergency response aspects of transportation tunnels, including transit, rail, and road [Ref. 27]:

14.3 Fixed Guideway Transit and Passenger Rail Systems
14.4 Rail Transportation Systems, and
14.7 Fire Protection for Road Tunnels.

PIARC has in its library of published documents a report entitled, "Fire and Smoke Control in Road Tunnels" [Ref. 27], which contains technical chapters providing guidelines on the following:

I. Objectives of Fire and Smoke Control,
II. Fire Risk and Design Fires,
III. Smoke Behavior,
IV. Study Methods,
V. Ventilation for Fire and Smoke Control,
VI. Exits and Other Safety Facilities,
VII. Tunnel Reaction and Resistance to Fire, and
VIII. Fire Response Management.

In addition, PIARC has a soon-to-be-published report entitled, "Systems and Equipment for Fire and Smoke Control in Road Tunnels" [Ref. 35], which will contain technical sections further addressing fire and emergency guidelines for tunnels, including the following sections:

- Smoke Progress at the Beginning of a Fire,
- Safety Concepts for Tunnel Fires,
- Lessons Learned from Recent Tunnel Fires,
- Ventilation,
- Emergency Exits in Enclosed Road Structures,
- Fire-Specific Equipment,
- Design Criteria for Structure Resistance to Fire, and
- Operational Responsibility for Emergencies.

The *Tunnel Engineering Handbook* [Ref. 25] provides six chapters addressing guidelines for the design of tunnel system elements:

Chapter 19: Fire Life Safety,
Chapter 20: Tunnel Ventilation,
Chapter 21: Tunnel Lighting,
Chapter 22: Power Supply and Distribution,
Chapter 23: Water Supply and Drainage Systems, and
Chapter 24: Surveillance and Control Systems.

The recently published *Handbook of Tunnel Fire Safety* [Ref. 26] contains five parts addressing the key elements of tunnel fire life safety:

Part I: Real Tunnel Fires,
Part II: Prevention and Protection,
Part III: Tunnel Fire Dynamics,
Part IV: Fire Safety Management and Human Factors, and
Part V: Emergency Procedures.

7.15 More Effective Fire Detection Systems

Using the results from research like that noted in Section 7.5, researchers could continue to develop more advanced detection systems. This effort will require a program to enlist the support, cooperation, and input from the industry, including manufacturers of fire detection equipment and systems.

7.16 Industry Feedback Workshops

A program to conduct several interactive feedback workshops could be developed at least 2 years after the implementation of this report to assess the impact of the report on tunnel safety and security. The primary function of these workshops would be to gather feedback from tunnel owners and operators on the implementation process and the successes and failures of the philosophy espoused in the report. This feedback could then be used to update and improve the report for later versions or to produce supplementary documents.

7.17 Interactive Electronic Version of this Report

The purpose of an interactive electronic version of this report would be to permit the tunnel owner or operator to more easily access the information contained herein. Specifically, a database that contains the structural and system vulnerability tables (Tables 14 through 16 and 25 through 27, respectively), the hazard and threat directories (Tables 28 through 33), the countermeasure guides (Tables 34 through 41), and the countermeasure descriptions (Sections 5.4.1 through 5.4.3) would allow the owner or operator to systematically go through the step-by-step process of identifying possible mitigation measures specific to his or her facility.

7.18 Effectiveness of Current Tunnel Fire Suppression Systems

Further research could evaluate the effectiveness of current fire suppression systems, including manual wet and dry standpipes and fixed systems. Manual wet and dry standpipes must be deployed by the incident responders. Fixed systems—such as sprinklers, deluge, and water mist systems—can be activated, either automatically or manually from a control center, prior to the arrival of the incident responders. Sprinkler and deluge systems can be water based or foam based and can be operated automatically or manually from a control center. Some work in this area is currently underway within PIARC and within the European community. A number of new and/or improved systems, such as water mist, are already under development.

7.19 Retrofit Technologies to Enhance Safety

Working with the industry, researchers could identify all retrofit technologies that, when applied to an existing transportation tunnel, will assist in addressing some of the issues identified herein. This research would have an overall positive impact on the safety and security of transportation tunnels.

7.20 More Effective Tunnel Fire Suppression Systems

Using the results of the research work being done by the NFPA and PIARC, researchers could continue to develop more advanced fire suppression systems. This effort will require a program to enlist the support, cooperation, and input from the industry, including manufacturers of fire suppression equipment and systems.

7.21 Tunnel-Specific Inspection Manual

A tunnel-specific inspection manual could assist the tunnel owner or operator in inspecting and surveying his or her specific tunnel and properly recording the inspection findings related to safety and security. The manual would be accompanied by associated database software. A suggested outline for such a manual is as follows:

1. Introduction
2. Purpose of inspection
3. Inspection requirements
   – Staffing
   – Equipment
4. Inspection protocol
5. Database development and management
6. Tunnel evaluations
   – Rating system
7. Conclusions
8. Appendixes

7.22 Advanced Coordinated Control Schemes for Ventilation Systems

Researchers could use the technology available to develop more advanced control systems for tunnel ventilation and fire protection systems.

7.23 Test Tunnels or Models

Researchers could build test tunnels or models to verify or measure structural damage from different explosions under security-related threats. Although this idea is good, conditions could change from project to project, resulting in too many variables. For example, test tunnels could be based on the principal types of tunnel construction, various types of surrounding earth, and/or underwater conditions. Several agencies are presently spending large amounts of money on nonlinear finite element blast analyses. Because test results may impact total project costs, this report would be a useful guide for engineers for future design work so that public funds could be spent effectively.

7.24 Structural Blast Damage Potential Analyses

At the present time, there are tremendous uncertainties in estimating and evaluating the relationship between varying hazard and threat levels (e.g., explosive weight) and damage potential to various types of tunnels and their structural elements. It is very difficult to adequately perform a tunnel vulnerability assessment based on available data without resorting to more refined analyses. Similarly, due to the lack of data, it is also difficult to properly develop warranted retrofit schemes and costs. Researchers could work on the development of more reliable empirical charts that relate explosive weight to structural damage potential. This research work could be approached in two ways: (1) in an analytical approach using blasting modeling and analyses and (2) in experimental field testing. It is anticipated that experimental testing would be carried out first to provide relevant calibration data for subsequent analytical work. Once the calibration analyses are completed, additional parametric runs could be efficiently and cost-effectively conducted to develop useful results.

7.25 Intelligent Egress Systems

Using the current computer modeling technology available in the egress area (e.g., Simulex), researchers could try to develop intelligent egress systems.

7.26 Issues Identified by Case Studies

Chapter 3 of this report summarizes a set of "lessons observed" from the tunnel incidents that have occurred around the world in recent years. These case studies could be researched further to obtain more specific information, especially in regard to the role that life safety systems played during the incident (see Table 5). This type of information could be extremely helpful to tunnel owners and operators faced with the decision of how best to allocate limited money to select countermeasures to increase the safety and security of their facilities.

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ADA	Americans with Disabilities Act
AISC	American Institute of Steel Construction
ANSI	American National Standards Institute
APR	Air-Purifying Respirator
AREMA	American Railway Engineering and Maintenance Association
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ATM	Asynchronous Transfer Mode
ATMB	Autoroutes et Tunnels du Mont Blanc (the French agency that jointly operates the Mont Blanc Tunnel with the Italian agency SITMB)
ATS	Austrian Schillings
AUA	American Underground Construction Association
AWS	American Welding Society
BART	Bay Area Rapid Transit
B&O	Baltimore & Ohio
BTP	British Transport Police
C/B/R	Chemical/Biological/Radiological
CCTV	Closed-Circuit Television
CCVE	Closed-Circuit Video Equipment
CM	Countermeasure
Comms	Communications
COSUF	Committee on Operational Safety of Underground Facilities
CPT	Cone Penetration Test
CTA	Chicago Transit Authority
°C	Degrees Celsius
DARTS	Durable and Reliable Tunnel Structures
DHS	Department of Homeland Security
DOT	Department of Transportation
DP	Damage Potential
EIA	Electronics Industries Association
EPB	Earth Pressure Balance
EPS	Expandable Polystyrene
ERP	Emergency Response Plan
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIT	Fire in Tunnels
°F	Degrees Fahrenheit
GA	Tabun
GB	Sarin
GD	Soman
HazMat	Hazardous Material
HVAC	Heating, Ventilating, and Air Conditioning
IBTTA	International Bridge, Tunnel and Turnpike Association
ICS	Incident Command System
IDS	Intrusion Detection System
IEC	International Electrotechnical Commission
IED	Improvised Explosive Device
IEEE	Institute of Electrical and Electronics Engineers
IEMA	Illinois Emergency Management Agency
ITA	International Tunnelling Association
km	Kilometer
LAN	Local Area Network
m	Meter
MARC	Maryland Area Rail Commuter
MBTU	Million British Thermal Units
MCEER (formerly NCEER)	Multidisciplinary Center for Earthquake Engineering Research (formerly the National Center for Earthquake Engineering Research, located at the University of Buffalo)
MEC	Mechanical, Electrical, and Communications
MOA	Memorandum of Agreement

MOU	Memorandum of Understanding
MTA	Maryland Transit Administration
MTFVTP	Memorial Tunnel Fire Ventilation Test Program
MW	Megawatts
NCEER	National Center for Earthquake Engineering Research
NFPA	National Fire Protection Association
NRCC	National Research Council of Canada
NTSB	National Transportation Safety Board
OV	Operational Vulnerability
PATH	Port Authority Trans-Hudson
PCB	Polychlorinated Biphenyl
PIARC	World Road Association
PUC	Public Utilities Commission
PV	Physical Vulnerability
PVC	Polyvinyl Chloride
RFP	Reinforced Fiber Protection
SCADA	Supervisory Control and Data Acquisition
SCBA	Self-Contained Breathing Apparatus
SEM	Sequential Excavation Method
SITMB	Società Italia per l`Esercizio del Traforo del Monte Bianco (Italian agency that jointly operates the Mont Blanc Tunnel with the French agency ATMB)
SONET	Synchronous Optical Network
SPT	Standard Penetration Test
TBM	Tunnel Boring Machine
TNT	2,4,6-Trinitrotoluene
TSA	Transportation Security Administration
UPTUN	UPgrading Methods for Fire Safety in Existing TUNnels
USDOJ	United States Department of Justice
Vent	Ventilation
VoIP	Voice-Over Internet Protocol
WTC	World Trade Center
VX	V Agent

Abbreviations and acronyms used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation