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.