U.S. Department of Transportation

Federal Railroad Administration

Characterization of Railroad Bridge Service Interruptions

Office of Research and Development
Washington, DC 20590

DOT/FRA/ORD-13/05

Final Report
February 2013

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE February 2013	3. REPORT TYPE AND DATES COVERED Technical Report	
4. TITLE AND SUBTITLE Characterization of Railroad Bridge Service Interruptions			5. FUNDING NUMBERS DTFR53-00-C-00012 Task Order 236
6. AUTHOR(S) Richard Joy, Mary Clara Jones, Duane Otter, and Luis Maal			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Transportation Technology Center, Inc. 55500 DOT Road Pueblo, CO 81001-0130			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Research and Development 1200 New Jersey Avenue, SE Washington, DC 20590			10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-13/05
11. SUPPLEMENTARY NOTES Program Manager: Monique Stewart			
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the FRA Web site at http://www.fra.dot.gov.			12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) The Federal Railroad Administration contracted Transportation Technology Center, Inc., to study bridge problems that cause accidents or service interruptions and to use this information to evaluate the need to develop bridge monitoring systems. Existing monitoring systems and other mitigation techniques were also considered. An analysis examining frequency and severity of the events estimates that the annual risk exposure from bridge defects is about $98 million excluding costs of resulting train delays. The largest contributors are scour, hydraulic problems, and strikes from marine and highway traffic. Another major contributor is damage from derailed trains, fires, failed structural members, and moveable bridge problems. A risk control matrix was developed to match potential problems with existing control measures and identify areas in which additional controls may be warranted. Results suggest that 1) protection systems are more effective than monitoring; 2) bridge inspection is an effective control for many potential losses; and 3) significant opportunity exists for defects to be detected by others working on the railway. This may indicate that training for recognition of bridge defects may be a cost-effective way of reducing losses from accidents and service interruptions. Additionally, track displacement detectors, tilt monitors, and midspan displacement monitors should be considered for investigation.			
14. SUBJECT TERMS bridge problems, risk control matrix, Railroad Bridge Service Interruption Database			15. NUMBER OF PAGES 74
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches	0			1		2			3		4		5	
Centimeters	0	1	2	3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgments

The authors express appreciation to all of those who helped with this investigation. Thanks to our technical advisory group for reviewing results and key assumptions and providing ideas, guidance and support: Mike Coltman and John Choros of the John A. Volpe National Transportation Systems Center; Steve Millsap of Burlington Northern Santa Fe Railway Company; John Unsworth of Canadian Pacific Railway; Jim Carter of Norfolk Southern (NS) Corporation; Mike Freeman of Union Pacific Railroad; and Gordon Davids of Federal Railroad Administration Office of Safety.

Thanks also to Jim Richter and Rene Asuncion of Amtrak and to David Bonas, Tom Heinrich, and Hugh Hyder of NS for their contributions.

Contents

Executive Summary 1

1 Introduction 3
- 1.1 Background 3
- 1.2 Objectives 5
- 1.3 Overall Approach 5
- 1.4 Scope 5
- 1.5 Limitations 6
- 1.6 Organization of the Report 6

2 Approach 7
- 2.1 Review Industry Literature 7
- 2.2 Query FRA Database 7
- 2.3 Interview FRA and Industry Experts 7
- 2.4 Establish Railway Bridge Service Interruption Database 7
- 2.5 Characterize Bridge Problems 7
- 2.6 Economic Analysis 8

3 Literature Review 9
- 3.1 Selected References 9
- 3.2 Mitigation Techniques 9
- 3.3 Other Programs to Characterize Bridge-Related Service Interruptions 14

4 Railway Bridge Service Interruption Database 15
- 4.1 Input from FRA Safety Database 17
- 4.2 Input from Railroad Industry 19

5 Primary Hazards/Precursor Events 20

6 Characterization of Bridge Problems 22
- 6.1 Ranking of Primary Hazards by Frequency 22
- 6.2 Events Resulting in Train Accidents 24
- 6.3 Damage from External Means 24
- 6.4 Annual Risk Exposure 25
- 6.5 Annual Risk Exposure 28
- 6.6 Risk Control Matrix 30

7 Economic Analysis 37
- 7.1 Upper Limit of Preventable Annual Risk Exposure 37
- 7.2 CBA of Selected Monitoring Systems 38
- 7.3 Assumptions and Estimations 39
- 7.4 Summary of Economic Analysis 40

8 Summary 42

9 Recommendations 46

10 References 47

Appendix A. Risk Control Matrix 51

Appendix B. Preventable Annual Risk Exposure for Selected Systems 55

Abbreviations and Acronyms 65

Illustrations

Figure 1. Frequency of FRA Reportable Accidents 18
Figure 2. Frequency of Railroad Reported Events 19
Figure 3. Frequency of Industry Bridge Related Service Interruptions 22
Figure 4. Frequency of Railroad Bridge Failures 23
Figure 5. Highway Bridge Failures in United States from 1966 to 2005 (presented by Briaud – Texas Transportation Institute) 24
Figure 6. Percentage of Failures due to Bridge Deficiencies and External Means 25
Figure 7. Ranking of Primary Hazards by Annual Risk – All Data 29
Figure 8. Ranking of Primary Hazards by Annual Risk – 1999-2010 Data 30
Figure 9. Excerpt from Risk Control Matrix 31
Figure 10. Risk Control Matrix Summary 36
Figure 11. Potential Preventable Annual Risk Exposure by Technology 38
Figure 12. Maximum Cost per Bridge for Technology to Breakeven 40
Figure 13. Maximum per Bridge Cost of Track Displacement Detector if Installed on 10 or 25 Percent of Bridges 41

Tables

Table 1. RBSID Key Fields 16
Table 2. High-Consequence FRA Reportable Accidents from 1980 to 1998 18
Table 3. Primary Hazards 20
Table 4. Basis for Assigned Loss Values 26
Table 5. Description of Severity Categories 27
Table 6. Source of Service Interruption Data by Category 27
Table 7. Potential Losses Due to Primary Hazards 33
Table 8. Bridge Protection Systems 34
Table 9. Scheduled Inspections 34
Table 10. Existing Detection Systems 35
Table 11. Advanced/Prospective Mitigation Techniques 35
Table 12. Top 15 Primary Hazards by Frequency 43
Table 13. Summary of Annual Risk Exposure 44

Executive Summary

The Federal Railroad Administration (FRA) contracted Transportation Technology Center, Inc. (TTCI), to study the types of bridge problems that cause accidents or service interruptions and to use this information to evaluate the need to develop new bridge monitoring systems. Existing monitoring systems and other mitigation techniques were also considered.

Data were gathered from the FRA Safety Database, from available railroad company records, and from interviews with industry experts. Analysts then developed a preliminary ranking of hazards based on frequency and severity of resulting accidents or service interruptions.

According to the data, the highest number of accidents and service interruptions resulted from bridge strikes from highway vehicles and from problems relating to moveable bridge signals. Because these are generally low-consequence events, however, they may not represent the problems with the greatest overall effect on the railroad industry.

The analysis, which considers both frequency and severity of bridge-related incidents, estimates that the annual risk exposure from bridge problems is approximately $98 million. The largest contributor is scour from moving water, combined with other bridge hydraulic problems at about $26 million per year. Next in rank are strikes from marine traffic at about $22 million per year and strikes from highway vehicles at about $11 million per year. Another large contributor is damage caused by derailed trains, fires, failed structural members, and moveable bridge problems.

Over 25 percent of the $98 million is attributable to four significant accidents that occurred between 1982 and 1997. No risk exposure events of this magnitude have occurred since 1997. This simplified approach does not consider improved procedures put in place by railroads and other entities since the events have occurred.

A risk control matrix was developed to match potential problems with existing control measures and to identify those areas where additional controls may be warranted. Results suggest that:

- Protection systems are likely more effective than monitoring.
- Bridge inspection is an effective control for many potential losses. It is currently the first line of defense for the railroads.
- Significant opportunity exists for defects to be discovered by others working on the railway. This may indicate that training for recognition of bridge defects may be a cost-effective way of reducing losses from bridge accidents and service interruptions.
- Track displacement detectors, tilt monitors, and midspan displacement monitors should be considered for additional investigation.

The estimates of risk exposure were used for a preliminary economic analysis of 15 potential monitoring systems. Of the 15 systems considered, 7 had annual upper limits of preventable annual risk exposure between approximately $13 and $36 million. The remaining eight systems had annual upper limits of approximately $5 million or less.

To provide a comparison of potential systems, a basic cost-benefit analysis (CBA) was conducted on six of the seven selected potential monitoring systems. The analysis considered

the maximum initial cost per bridge that could be spent on a system based on the preventable annual risk exposure. Results indicate that for implementation of any of the systems to be cost-effective, a selective implementation strategy would be required. Across-the-board implementation would not be cost-effective.

The estimates of costs reported here were used to rank the primary hazards. Costs of train delays, traffic diversions, and business loss are not included. These analyses are intended for initial comparisons only.

A literature review was carried out to identify existing and potential monitoring systems and to identify similar work that has been undertaken. An industry technical advisory group (TAG) was formed consisting of high-level railroad bridge engineers, the John A. Volpe National Transportation Systems Center (Volpe), and FRA.

Data were gathered from the FRA Safety Database, from available railroad company records, and from interviews with industry experts. Both FRA and railroad data lack detail. However, the available data were unified and collated in a Railroad Bridge Service Interruption Database (RBSID), which contains over 8,700 records. The database was created in Microsoft Access to allow for easy entry and query.

Additional work is proposed to develop a risk assessment method that would identify those bridges that will benefit most from having remote monitors installed and to identify technologies that can aid the inspection process. This might include improved nondestructive evaluation (NDE) techniques or bridge health monitoring technologies.

1. Introduction

The objective of this project was to gain a better understanding of the types of bridge problems that cause accidents or service interruptions and to use this information to evaluate the need to develop new bridge monitoring systems. Existing monitoring systems and other mitigation techniques were also considered.

1.1 Background

Recent events such as the I-35 highway bridge failure in Minneapolis, MN, and the railroad bridge accident in Myrtlewood, AL, have renewed interest in remote monitoring as a means of protecting critical infrastructure. In the United States, railroad bridges are a critical part of the transportation network. According to a recent FRA study there are over 1,760 miles of railroad bridges in the United States, including 418 miles of timber structures (1).Thousands of steel bridge spans approaching 100 years of age are still in service.

Commercial bridge monitoring systems are becoming more common. A recent survey documents 38 companies that supply bridge monitoring equipment (2). However, the survey authors caution that, although many of the systems come with claims that results would be immediately useful to the owner, much study is still needed to establish useful thresholds. The best information that most systems can offer today is a warning that changes have taken place.

1.1.1 New Regulations for Railway Bridges

In response to a series of train accidents caused by failures of timber bridges, FRA issued a safety advisory in September 2007 to supplement and re-emphasize the provisions of the Policy on the Safety of Railroad Bridges (3).

On October 16, 2008, the Rail Safety Improvement Act of 2008 was signed into law. The new regulations required railroad track owners to adopt and follow specific procedures to protect the safety of their bridges. In response, on August 17, 2009, new U.S. bridge safety regulations were formally proposed by FRA. These regulations were developed in cooperation with industry through a Rail Safety Advisory Committee. The Final Rule was published on July 15, 2010, as Title 49, Code of Federal Regulations, Part 237 (4).

1.1.2 Selected Significant Bridge Events

A number of key events on both highway and railroad bridges have driven bridge policy in the United States.

I-35 Bridge Failure – Minneapolis, MN

On August 1, 2007, a highway bridge carrying Interstate 35 over the Mississippi River in Minneapolis, MN, collapsed during rush hour traffic causing 13 fatalities. Since the accident, increased public awareness has created a renewed interest in critical infrastructure condition, management, and monitoring in the United States (5).

Railway Bridge Accident in Myrtlewood, AL

On May 2, 2007, a freight train carrying segments of the space shuttle's solid rocket boosters derailed in Myrtlewood, AL, after a timber trestle collapsed. The train comprised cars of exceptional weight and configuration and was operating without proper clearance from the track owner. This incident has been cited as a reason behind a new set of FRA regulations proposed in August 2009 (3).

Amtrak Derailment in Kingman, AZ

On August 9, 1997, in Kingman, AZ, an Amtrak train derailed as it was crossing a bridge. It was later determined that the bridge's supporting structure had been washed away by a flash flood (6).

Derailment on Portal Bridge in Secaucus, NJ

On November 23, 1996, Amtrak train No. 12 derailed while crossing Portal Bridge, a swing bridge spanning the Hackensack River in Secaucus, NJ. When the train derailed, it sideswiped Amtrak train No. 79, which was crossing the bridge in the opposite direction on an adjacent track. Cause for derailment was found to be defective rail-end transition devices (7).

Amtrak Accident on Big Bayou Canot Bridge near Mobile, AL

On September 22, 1993, an Amtrak train derailed because one span of the Big Bayou Canot Bridge near Mobile, AL, was out of alignment after being struck by a barge. The train arrived and derailed at the bridge less than 10 minutes after the incident. There were 103 injuries and 47 fatalities (8).

Failure of the Schoharie Creek Highway Bridge near Amsterdam, NY

On April 5, 1987, the Schoharie Creek Highway Bridge near Amsterdam, NY, failed because of scour damage at pier three of the bridge. Ten people were killed. It was later determined that the installation of riprap, used to protect from scour, had been cancelled. This accident motivated the improvement of bridge inspection, maintenance, and management practices (9).

Collapse of Route 95 Highway Bridge in Greenwich, CT

On June 28, 1983, the Route 95 Highway Bridge over the Mianus River in Greenwich, CT, collapsed, killing three people, because the pin and hanger assembly supporting the span failed (10).

Collapse of Silver Bridge between West Virginia and Ohio

On December 15, 1967, the Silver Bridge between Point Pleasant, WV, and Kanauga, OH, collapsed, killing 46, because of an eyebar failure. This accident led to legislation requiring a national bridge inventory, biennial inspections, inspector qualifications, and reporting requirements (11).

1.2 Objectives

The long-term objective of this project is to identify bridge monitoring systems that will warn bridge owners of possible structural damage, reduce the occurrence of bridge problems by providing early warning of bridge distress, and enable predictive maintenance on an aging bridge population.

1.3 Overall Approach

This work focused on developing detailed characterizations of the major drivers causing accidents or service interruptions. The first source of information was the FRA Safety Database, which records accidents involving train operations. In addition, available data from five major railroads were compiled. Also, the FRA Office of Safety was consulted to review and augment the available data. To encourage participation and cooperation, railroad names are not reported—industrywide summary information is used.

Simple risk analysis techniques and economic analyses were used to estimate what problems have the greatest effect on the industry and how bridge monitoring or other techniques may best be used to mitigate the problems. Existing railroad bridge monitoring systems, potential advanced monitoring systems, and other mitigation techniques were considered.

An industry TAG was established to guide the work.

1.4 Scope

The FRA Safety Database identifies bridge failures, but the cause codes do not focus narrowly enough to understand what is required to reduce risk in a particular area. Furthermore, only events above a damage cost threshold and involving train operation are included.

The RBSID compiled for this investigation includes data from the FRA Safety Database and from the railroads. Unlike the FRA data, railroad information includes major events that did not involve train operations such as bridge fires and bridge washouts. In addition, many less serious but frequent events are included. For example, bridge strikes by highway vehicles often result in little or no damage, but interrupt railroad traffic while inspections are carried out. The RBSID will be provided to FRA as part of the deliverables for this project.

The information compiled in the RBSID was used as the basis for a simplified risk analysis to show what types of events and hazards are having the greatest affect on the industry. A list of primary hazards driving the identified bridge problems was compiled. Existing and potential bridge monitoring systems and other mitigation techniques were matched to the primary hazards with the greatest effects.

The information compiled for the risk analysis was used for a preliminary economic analysis to estimate how much could reasonably be spent on implementation of selected monitoring systems and technologies. Results indicate that cost-effective implementation of any of the systems will require a selective implementation strategy. Across-the-board implementation would not be cost-effective. Additional work is recommended to design a structured, risk-based approach for selective implementation of monitoring systems.

1.5 Limitations

The simplified risk analysis in this report provides a reasonable insight into what has driven bridge-related accidents in recent years. Events compiled over the past 10 years provide a good picture of high-to-medium frequency, low-to-medium consequence events driving accidents and service interruptions.

High-consequence events such as the Big Bayou Canot or Kingman, AZ, accidents have been infrequent, particularly in recent years. This is largely due to railroad's incorporation of best practices in bridge inspection and management. Over the past 30 years, there have been only four of these high-consequence accidents. Once the annual risk was compiled, the cost was normalized over a 30-year period. This simplified approach does not consider improved procedures put in place by railroads and other entities since the events occurred.

A comprehensive analysis of potential high-consequence events would need to consider not only historical events but potential future events. Although methods exist for such an analysis, it is beyond the scope of this report. Any additional work for selective implementation of monitoring systems will need to use a structured approach to consider the possibility of events that have not been documented historically.

The risk analysis incorporated rough estimates of loss based on the bridge service interruption data compiled. Because of the large number of bridge events considered, a number of very general estimates were used. Where actual values of loss were available, a multiplier was used to account for indirect damage. It is recognized that indirect costs can vary widely. Total values are somewhat understated because the multiplier does not account for train delay, traffic diversion, and business loss costs. In the majority of cases in which actual values of loss were not available, a structured approach for applying order-of-magnitude estimates was applied.

The estimates of costs reported here were used to rank the primary hazards. These analyses are intended for initial comparisons only.

1.6 Organization of the Report

This report is organized into six main areas:

- Results from Industry Literature Review
- Railway Bridge Service Interruption Database
- Characterization of Bridge Problems
- Economic Analysis
- Summary
- Recommendations

2. Approach

To identify the types of bridge failures that cause accidents or service interruptions and to determine when and what type of monitoring is warranted, TTCI studied and characterized bridge risk factors and how these risk factors might be mitigated.

2.1 Review Industry Literature

A literature search was conducted to document existing and potential bridge protection, monitoring techniques, and other efforts that characterize causes of railway or highway bridge service interruptions.

2.2 Query FRA Database

The FRA Safety Database of rail-related accidents and other incidents was queried for bridge-related events. The available information is limited because the database generally contains only relatively serious accidents involving train operation.

2.3 Interview FRA and Industry Experts

An industry TAG was formed to provide feedback and direction in the project. The participating groups included Amtrak, Norfolk Southern Corp. (NS), Union Pacific Railroad (UP), Burlington Northern Santa Fe Railway Company (BNSF), Canadian Pacific Railway (CP), FRA Office of Research, FRA Office of Safety, and the John A. Volpe National Transportation Systems Center (Volpe). Periodically, the TAG was asked to comment on results and to review key assumptions used in the study.

In addition, followup interviews were carried out where required. The authors visited BNSF, NS, and Amtrak offices and held phone conversations with the FRA Office of Safety.

2.4 Establish Railway Bridge Service Interruption Database

Data from various sources were unified and collated into a useful form in the RBSID. Derailments from the FRA Safety Database and service interruptions provided by five major North American railroads are included. The RBSID contains over 8,700 records. It was created in Microsoft Access to allow for easy entry and query.

2.5 Characterize Bridge Problems

The RBSID was analyzed in detail to develop a characterization of the types of bridge problems that are causing accidents and service interruptions. A simplified risk analysis approach was used to identify the primary hazards most likely to result in accidents or service interruptions and to identify potential control or mitigation measures for these hazards.

2.6 Economic Analysis

A preliminary economic analysis was carried out for 15 selected potential monitoring systems likely to be the most effective. Information from the RBSID was used to establish an upper limit of the preventable annual risk exposure that each monitoring system might address. Then, discounted cash flow techniques were used to estimate how much spending could be justified for six of the most promising monitoring systems.

3. Literature Review

A literature review was conducted to review current and developing mitigation techniques. In addition, similar efforts to categorize bridge problems were reviewed. For convenience, information provided by the industry TAG is included in the report.

3.1 Selected References

The following references are excellent summaries of bridge monitoring needs and technologies and are most relevant to this investigation.

In 2009, the University of Minnesota prepared a report on bridge health monitoring methods for the Minnesota Department of Transportation (MNDOT) (2). The report is intended for highway bridge engineers. It is an excellent and current reference for railway bridge engineers as well. The report lists survey results from 38 companies that supply bridge monitoring equipment. The authors draw an important conclusion that although many companies offer complete monitoring systems that would be immediately useful to the owner, much work still needs to be done to establish useful thresholds. The best information that most systems can offer today is a warning that changes have taken place, which suggests that damage likely exists.

In 2008, the Transportation Research Board (TRB) published an article by Hunt on scour monitoring programs for bridge health (12). It reports on scour monitoring of four bridges that incorporated site-specific fixed scour monitoring. The scour monitoring included a fixed sonar system for tidal-cold weather environment, a multiple station sonar system, and a scour monitoring program manual. The scour monitoring program reviewed available data (historic, current, and potential) to evaluate scour conditions, performed a hydraulic, scour, and stability analysis of the bridge, and evaluated scour countermeasure alternatives. Most notable for this evaluation was a general discussion highlighting lessons learned from past scour monitoring and trends in scour monitoring technology.

The International Heavy Haul Association included an article on Bridge Health Monitoring in its *Guidelines to Best Practices for Heavy Haul Railway Operations* (13). It provides an excellent overview of railroad bridge monitoring systems currently being used in North America and is cited several times in this report.

In 1994, FRA conducted a study on railroad bridges to assess techniques and technologies for automatic monitoring of railroad bridge integrity for the purpose of reducing the number of bridge-related train accidents (14). Results indicated that widespread installation of bridge monitoring devices was not economically feasible. However, the study did not rule out bridge integrity monitoring on bridges highly vulnerable to damage.

3.2 Mitigation Techniques

For the purpose of this investigation, mitigation techniques were categorized as bridge protection methods, scheduled inspections, existing monitoring systems, and advanced or prospective mitigation techniques.

Davids of the FRA Office of Safety emphasizes that good bridge inspections are the first and last line of defense against bridge failures, catastrophic and otherwise (15). Davids points out that bridges do not often just fail without warning indications, and the purpose of a bridge inspection is to find those indications before they turn into serious problems. Inspections should be scheduled at a sufficient frequency and a level of detail that these indications can be found in time. Highway bridges are required to be inspected once every 2 years. Davids notes that an industry standard of annual inspections for railroad bridges dates back more than 100 years. This standard has recently been incorporated into the Final Rule on Railroad Bridge Safety (4).

Bridge protection methods generally provide high value because they can prevent damage from occurring rather than just reporting that is has occurred. Similarly, some bridge monitoring techniques can provide advance warning to identify potential problems and warn the train operator that a hazard exists. Traffic can be stopped through a radio alarm, signal system, or notification sent to the dispatcher.

Other monitoring systems provide an indication of a bridge's overall health. Otter and Carr suggest that these systems provide a great deal of data and require interpretation of results by a bridge engineer (13).

3.2.1 Bridge Protection Methods

Bridge protection methods generally refer to physical barriers to bridge damage. Techniques for protection against bridge strikes include protecting the piers with crash walls, barrels, beam guardrail, cable, and/or concrete (16). Waterway bridge protection methods are used to protect bridges that cross or are near navigable waterways. Appropriate lighting is required per U.S. Coast Guard regulations. Bridges near or at these waterways typically use fenders to protect bridge piers from barge and ice or drift strikes (13).

Several other bridge protection methods are available. Sacrificial beams are used in some cases to protect bridges from overheight vehicles. Signage, lighting, painting, pavement markings, and telltales have also been used on roadways approaching low-clearance overhead railroad bridges. The industry TAG identified inner guardrails, truss guardrails, and truss collision posts as common means of preventing or minimizing bridge damage from derailed trains.

3.2.2 Scheduled Inspections

The American Railway Engineering and Maintenance and Way Association (AREMA) has recently published a comprehensive bridge inspection handbook (17). The handbook covers all facets of railway bridge inspections, such as special inspections after fires, floods, derailments, or earthquakes. A recent paper by Sweeney and Unsworth provides details of inspection programs for two large North American railroads (18).

For highway bridges, the National Cooperative Highway Research Program has published a report on bridge inspection practices in the United States and selected foreign countries (19). It is a collection of information on formal inspection practices of departments of transportation. Information is presented on inspection personnel, inspection types, and inspection quality control and quality assurance.

The industry TAG indicates that some railroads are training track inspectors to carry out basic bridge inspections as part of their regular duties as a way to supplement their bridge inspection programs.

Detailed inspections of moveable bridges usually require a team of inspectors with one each from mechanical, electrical, and structural disciplines (17). The industry TAG notes that many of the moveable bridge problems are reported by either local or remote bridge tenders or operators. In addition, moveable bridge problems are often detected as a signal system interlocking failure.

NDE methods such as dye penetrant and ultrasonic inspection are often used to supplement scheduled inspections of railroad bridges. A new program developed by the Federal Highway Administration (FHWA) presents a 1-day seminar to provide formal training to bridge inspectors in the basic principles and general operational procedures of five of the latest portable, technician-driven NDE technologies: (1) ultrasonic testing, (2) eddy current, (3) ground penetrating radar, (4) impact echo, and (5) infrared thermography (20). These technologies are intended to supplement scheduled bridge inspections on an ongoing basis.

Underwater inspections are critical on many bridges. The AREMA *Bridge Inspection Handbook* notes that the need for and frequency of underwater inspections is determined by an engineer for any structure having continuously submerged components (17).

3.2.3 Existing Detection Systems

A number of existing detection systems are either currently being used on bridges or can be adapted for such use. Otter and Carr identify shifted load and high or wide load detection and dragging equipment detection as technologies that are commonly being used in North America (13).

High-water detectors are advance warning systems where train crews, maintainers, and other personnel can be alerted to high water at a particular bridge. High-water detectors are potentially useful in identifying conditions likely for scour to occur. These systems can be connected through a radio alarm, signal system, or notification sent to the dispatcher to stop traffic if necessary, often based on a threshold monitoring value (13).

Shifted load and high or wide load detection systems are used to prevent bridge strikes where a rail vehicle does not have enough clearance for the bridge or tunnel. These systems check vehicles or loads that are too large to safely clear the bridge or tunnel. Again, radio or other notification can be used to stop the train (13).

Dragging equipment detectors identify railcars that could cause significant damage to a bridge. These detectors are very useful in identifying derailed wheels (13).

The industry TAG points out that the rail-break circuit of the signal system can also be considered a bridge monitoring device, because identification of a rail break on or near a bridge can prevent potential damage from a train derailment.

Load monitoring is an important tool used to monitor bridges. For many bridges, the load rating for the bridge when installed is inadequate today or will be inadequate with increased axle loads or increased traffic. Chase and Laman discuss several technologies that have been used to monitor loads in bridges including piezoelectric sensors (ceramic and polymetric), optical sensors (microbend and Bragg grating), and interferometric (21). Otter and Jones describe an Association of American Railroads' (AAR) program to measure the load traffic on railroad bridges (22). A wayside detector that measures vertical load (wheel impact load detector) is used to estimate the vertical load railroad cars are putting on bridges. Witte et al. describe how wheel impact load detectors can be used to detect imbalanced loads, which can reduce bridge life over time (23).

Damage to bridges due to train accidents caused by track buckling on approaches is a significant problem. Track buckling occurs in continuous welded rail when high compressive forces build up. Rail strain monitoring technologies can identify track conditions where high compressive loads exist. Read describes a number of technologies that exist to monitor rail strain (24). Electrical resistance strain gages are simple to install but require cutting of the rail to obtain a calibration when the rail is unloaded. These systems are capable of continuous monitoring but are location specific and cannot be moved to a different location. Some are equipped with radio freqency technology to allow remote monitoring.

Picton Technologies has developed a simple technology that can provide warning of an unacceptable track displacement (25). It is based on a simple contact switch that is broken after a predetermined deflection. The switch can be integrated with the current signal system.

Reece et al. describe how geographic information system (GIS)based weather notification networks that can provide automated warnings of severe weather to railroad dispatch centers are being used by major North American railroads (26). The GIS notifications are location specific, which allow the railroad to take early action such as delaying trains or dispatching inspectors to avoid accidents. Notifications of heavy storms that may result in flash floods are particularly applicable to bridges.

Railroads in North America rely on earthquake notifications systems to provide automatic notification of significant earthquakes (27) Guidelines for post earthquake operation are provided in the AREMA *Manual for Railway Engineering*, Chapter 9 (28).

The industry TAG points out that many bridge problems are found by those other than bridge inspectors, i.e., track inspectors, bridge tenders, locomotive engineers, signalmen, or others, while carrying out their normal duties. One Class 1 railroad has prepared a training course for track inspectors on how to detect potential water-caused problems. This has proved very effective with regard to high water, blocked water courses, etc.

3.2.4 Advanced or Prospective Mitigation Techniques

A number of advanced or prospective mitigation techniques were considered based on the literature and discussions with the industry TAG. The set of techniques considered for further evaluation is not exhaustive but covers many concepts being considered by the industry.

Strainstall offers a detector to identify when a bridge strike occurs; however, these are not widely used in the United States (13, 29).

Deflection of a bridge span under loads is often considered an important parameter for bridge performance evaluation. However, it is often inconvenient to obtain the bridge deflections directly. Difficult access when bridges cross rivers, other railways, or highways makes a direct measurement impractical. Gindy et al. report on an experiment to use integrated acceleration to measure deflection in these difficult areas (30). To date, sensor drift, unknown initial bridge conditions, and dynamic coupling with the traffic loads have proved these measurements to be unreliable. However, MNDOT reports that several companies claim to offer displacement measurements and data interpretation (2).

Hunt describes several methods for unattended scour monitoring (12).

- Sonar scour monitors, which are mounted onto the pier or abutment face and connected to data loggers. These monitors track the scour and refill process.
- Magnetic sliding collars are rods attached to the pier or abutment face with sliding magnetic collars that rest on the streambed. Should the streambed erode, the collars move downward. These devices measure the maximum depth of scour rather than the scour and refill process.
- Float-out devices are buried at various depths near the substructure. If scour develops, the devices float to the surface and transmit a signal.
- Tiltmeters and vibration meters to monitor bridge movement.

A scour monitoring system may be a single device or a combination of the above devices. Data may be downloaded at the site or transmitted to a central location.

Strain measurement techniques are often used on steel bridges to quantify actual stresses in problem areas identified during bridge rating. Najjar et al. and Kober et al. provide excellent case studies (31, 32). Often the mesured stresses are significantly less than those calculated because of unexpected member load sharing, etc. MNDOT reports that a several companies are now offering systems that use strain measurement as part of a global health monitoring system (2).

Hunt reports that tilt monitors can be used as part of a scour monitoring system to detect gradual movements of foundations (12). MNDOT suggests that because inclination must be known at more than one point on a bridge to provide usable information, a single tilt monitor would not be a viable bridge monitoring method (2), although several vendors offer tilt monitoring as part of a bridge monitoring system.

Monitoring systems mounted on bridges have a built-in limitation in that they can only monitor the bridge they are installed on. The industry is interested in developing a vehicle-borne system that can detect bridge problems as it travels over the system. AAR is investigating the feasibility of such a system under its Strategic Research Initiatives. Arnold et al. have developed a system that measures track modulus from a moving rail car (33). Analysis of these data has been able to identify weak track at bridge approaches. There may be potential to adapt such a system to identify unacceptable deflection of bridges.

3.3 Other Programs to Characterize Bridge-Related Service Interruptions

FHWA has initiated a Long-Term Bridge Performance (LTBP) Program to collect nationwide data on highway bridges (34). This will be a 20-year research effort. Data will be collected from different sources including legacy data, detailed visual inspection reports, environmental information, and monitoring or instrumentation data. To efficiently manage, organize, and use this vast amount of data, LTBP is developing an open, scalable, and extensive data management and analysis infrastructure.

Stein and Sedmera report on a 2006 study of risk-based management guidelines for scour. The work was sponsored by the American Association of State Highway and Transportation Officials in cooperation with the FHWA (35). This program developed guidelines to select a management plan for preventing scour failure for bridges with unknown foundations. The guidelines included collecting appropriate data, estimating risk of failure, and selecting a bridge management approach.

The Rail Safety and Standards Board in the United Kingdom published a report analyzing the rising trend in the number of reported bridge strikes from 1994 to 2001, with the aim of understanding the reasons for this trend (36). On average, 30 bridge strikes occur each week over the British railway system, approximately 96 percent of which result in little or no consequential damage.

In its report on bridge monitoring methods, MNDOT included a systematic methodology for matching bridge monitoring needs with available technologies, using a Microsoft Excel spreadsheet program.[2]

4. Railway Bridge Service Interruption Database

The RBSID contains information on over 8,700 accidents and service interruptions based on FRA and industry records. Industry records were included specifically to capture service interruptions not included in the FRA database and to clarify some ambiguous entries. The information is in a Microsoft Access database.

A record is filed for each event that resulted in an accident or service interruption. Each record contains 29 data fields that have been completed based on the availability of data. Table 1 lists the fields with a brief description of each.

Table 1. RBSID Fields

Field	Description
Incident Number	Unique reference number
Service Interruption (Yes/No)	Did the event cause a service interruption?
Length of Service Interruption (hour)	If known
Primary Hazard	Primary hazard as described in Section 5
Type of Damage	If known — bridge collapse/partial collapse, misalignment, damage to substructure, damage to superstructure, etc.
Severity	Category 1, 2, 3, or 4
Cause 1	Allows for additional explanation of cause
Cause 2	Allows for additional explanation of cause
Cause 3	Allows for additional explanation of cause
Year	Year event took place
Source of Incident Data	Source of data -- Railroad, FRA, or other
Source of Report	If known — how was event reported -- dispatcher, citizen call-in, bridge inspector, etc.
Equipment Damage ($)	If known — cost of equipment damage
Track Damage ($)	If known — cost of track damage
Total Property Damage ($)	If known — total cost of property damage
Number of Injuries	Self-explanatory
Number of Fatalities	Self-explanatory
Super Structure Material	If known — steel, timber, etc.
Super Structure Type	If known — girder, truss, beam, etc.
Substructure Type	If known — deep foundation, shallow foundation, other
Moveable	Yes or no
If Moveable, what type?	Bascule, vertical lift, etc.
Deck Type	Open deck, ballast deck, other
Feature Crossed	Other railroad, highway, navigable waterway, etc.
Height Clearance (ft)	If known
Short Description of Incident	As available — modified as necessary to avoid revealing railroad names
Comments	Allows authors to add comments

4.1 Input from FRA Safety Database

FRA maintains a Safety Database on rail-related accident and incident occurrences. Anyone may download this data from the FRA Web site (37). All accidents or incidents that involve rail equipment in the United States and result in equipment and track damage greater than a dollar threshold set annually by FRA must be reported and included in the database. With a few exceptions, bridge problems that do not involve a train, such as a washout or a fire, are not included. Threshold dollar values range from $6,700 in 1999 to $9,200 in 2010. Reporting requirements are described in the proposed "FRA Guide for Preparing Accident/Incident Reports (38)."

The most important FRA Safety Database entries for this investigation include accident causes, estimated dollar amount of equipment and track damage, total property damage, and the number of fatalities and injuries. A short narrative description is also provided, which was essential to extracting bridge-related events.

There are 389 cause codes used in the FRA Safety Database ranging from mechanical failure codes to human error codes. Some examples are: cause code E30C — *Knuckle Broken or Defective*, cause code M201 — *Load Shifted*, and cause code T201 —*Broken Rail – Bolt Hole Crack or Break*. The only cause code specifically used for bridges is T401 — *Bridge Misalignment or Failure*. Cause code T499 — *Other Way and Structure Defect with Detailed Description* is sometimes used for bridge problems. However, many accidents involving bridges are listed under other codes.

All accidents for the appropriate period were downloaded from the database. The data were queried for the two bridge-related cause codes. However, many additional accidents involving bridges were found by searching the narratives for the key word "bridge." Many of these accidents were due to external means. One example would be a train derailment caused by a burned off bearing where a bridge was struck and damaged. This accident would be listed with a mechanical failure code. It could only be identified as a bridge-related event by searching the narrative by key word. Some accidents involving bridges had no reference to a bridge but were found by correlating FRA data with railroad-supplied data.

All bridge-related accidents from the period from January 1999 to March 2010 are included in the RBSID. No high-consequence events such as the Big Bayou Canot or Kingman, AZ, accidents occurred during this period.

An additional query for accidents with an estimated total cost over $20 million over the period between January 1980 and December 1998 revealed four of these high-consequence accidents. Table 2 shows these accidents. These accidents have also been included in the RBSID.

The Myrtlewood, AL, accident is included in the 1999–2010 data, but the total cost is significantly less than $20 million.

Table 2. High-Consequence FRA Reportable Accidents from 1980 to 1998

Year	Description	Estimated Cost (millions — 2010 dollars)	Injuries/ Fatalities
1982	Derailed six cars due to bridge washout and excessive speed for conditions.	$20.9	15/0
1993	Train derailed because one span of the Big Bayou Canot bridge near Mobile, AL was out of alignment after being struck by a barge	$436.2	103/47
1996	Train with two engines and 12 cars derailed the entire consist at Portal Bridge, Secaucus, NJ. As train was derailing, it sideswiped westbound train	$64.1	43/0
1997	Derailed 15 cars on bridge in Kingman, AZ, which had been damaged by runoff because of heavy rain	$242.1	183/0

Figure 1 shows the number of bridge-related accidents from 1982 to March 2010 by the related primary hazard. There were a total of 177 accidents. The highest number of accidents (22 percent) was caused by derailed trains, followed by load shift (9 percent).

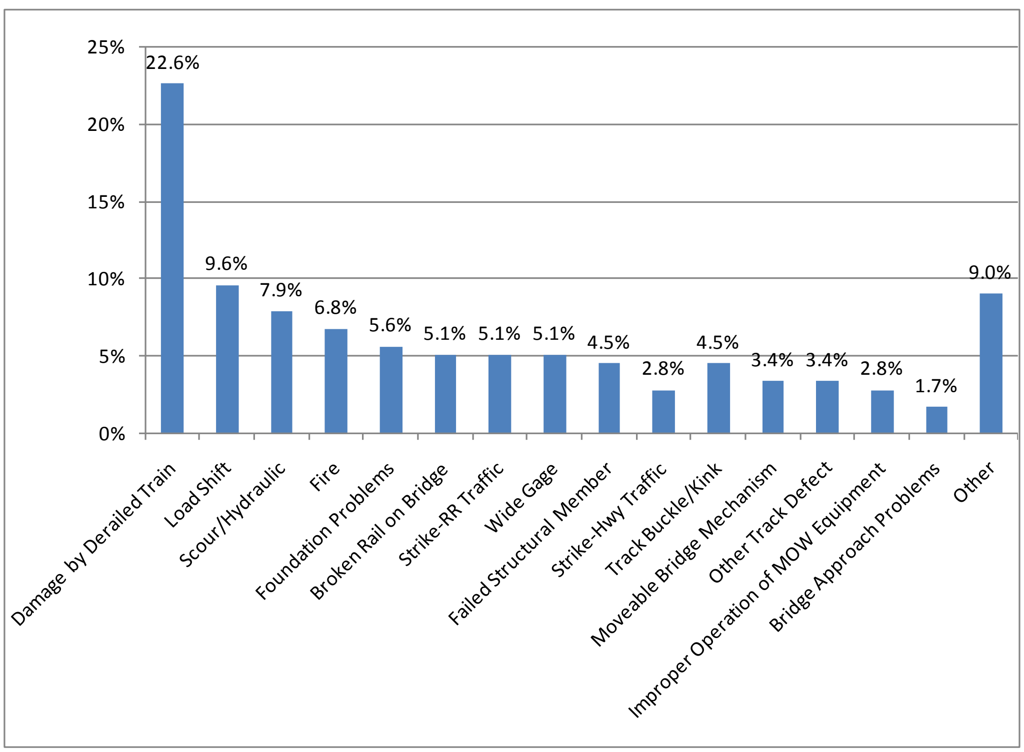

Figure 1. Frequency of FRA Reportable Accidents

4.2 Input from Railroad Industry

Bridge service interruption data were provided by five major railroads, and it greatly expanded the data from the FRA Safety Database. Unlike the FRA data, many events not directly caused by the movement of trains such as fires and bridge washouts were included. In addition, data from the railroads included many lower-consequence events with damage less than the threshold for FRA reporting.

As part of the data-gathering process, the TTCI team visited three Class 1 railroad offices and interviewed senior bridge engineers. The industry data collected varied widely from railroad to railroad. Some railroads provided detailed description of each service delay including the delay time, whereas others provided input based on the recollection of key personnel. Where data were based on recollection, an estimate of annual service interruptions was compiled, with estimates of severity and the underlying cause. These estimates were extrapolated over 10 years and included in the RBSID.

There is little railroad data available that is older than 10 years, and the available data generally lack detail. Costs are not available in most cases.

Figure 2 provides a summary of industry bridge-related service interruptions. There are a total of 8,563 events reported. The highest frequency event is strikes by highway vehicles representing approximately 50 percent of the data.

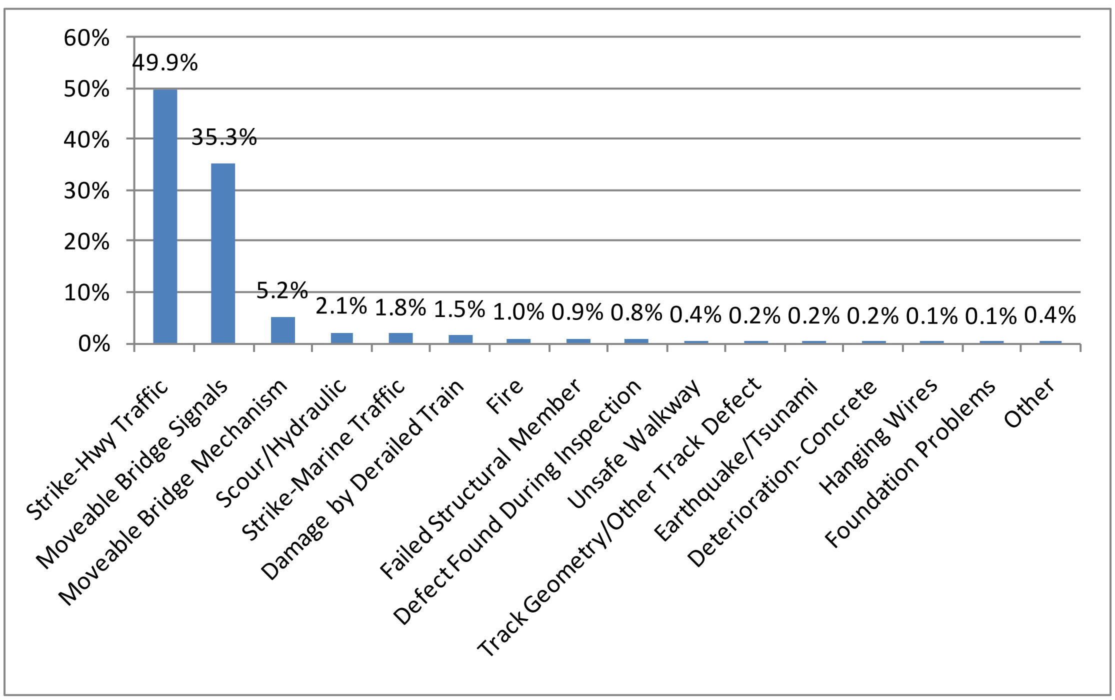

Figure 2. Frequency of Railroad Reported Events

5. Primary Hazards/Precursor Events

The study conducted by FRA in 1994 listed 15 initiating causes of bridge accidents. Because service interruptions as well as accidents are included, the list was expanded as the events in the RBSID were analyzed. A number of additional hazards were included based on suggestions from the industry TAG.

For the purpose of this investigation, these precursor events or conditions are referred to as primary hazards. The authors have attempted to group similar hazards where appropriate, while leaving those hazards with unique features separate. Table 3 lists the 43 primary hazards identified.

Table 3. Primary Hazards

Primary Hazard	
Bridge Approach Problems	Load Shift
Bridge Misalignment	Bridge Strike—Marine Traffic
Broken Rail on Bridge	Moveable Bridge Mechanism
Corrosion (steel structures)	Moveable Bridge Signals
Decay/Rot (timber structures)	Mudslide/Landslide
Defect Found during Inspection	Other Hydraulic—Bridge
Damage by Derailed Train	Other Track Defect
Deterioration—Concrete	Overload
Earthquake/Tsunami	Rail Car Defect
Failed Structural Member	Bridge Strike—Railroad Traffic
Falling Debris	Sabotage/Explosion
Fatigue(steel structures)	Scour
Fire	Storm/Hurricane
Foundation Problems	Structural Damage Because of Vandalism
Hanging Wires	Track Buckle/Kink
High/Wide Rail Carload on Bridge	Track Geometry
Bridge Strike—Highway Traffic	Track Washout
Hydraulic—Approach	Unknown
Imbalanced Load	Unsafe Walkway
Improper Design/Construction	Wide Gage
Improper Operation of Maintenance of Way Equipment	Wind

Problems related to high water are separated into three primary hazards: (1) *Scour*, (2) *Other Hydraulic—Bridge*, and (3) *Hydraulic—Approach*. *Scour* implies an undermining of the foundation because of high flows. *Other Hydraulic—Bridge* includes bridge washouts, ice, or debris buildup or poorly described high-water problems. *Hydraulic—Approach* refers to a washout or other high-water damage to the bridge approach.

There are many events in the RBSID having multiple causes or lacking details that would point to a cause. An attempt was made to associate every event with a primary hazard. FRA Office of Safety was consulted and, in many cases, provided sufficient clarification to identify a primary hazard. However, in six cases engineering judgment was insufficient, and the primary hazard was listed as unknown.

Also, there are several cases in which one could arguably combine several primary hazards under a single heading or split a hazard into several subheadings. For example, *Track Buckle/Kink*, *Track Geometry*, *Track Washout*, and *Wide Gage* could be combined under the heading of *Derailed Train*. However, in this case, the authors decided to keep them separate. Damage from a derailed train is likely to be the result of a mechanical problem or another problem that occurs far from the bridge. Sun kinks, wide gage, and other track geometry issues are problems occurring at the bridge or approach.

6. Characterization of Bridge Problems

The RBSID was analyzed in detail to develop a characterization of the types of bridge problems that are causing service interruptions. The analysis was meant to reduce the list of primary hazards from a list of 43 to a more manageable number. Similarly, the analysis identifies several mitigation techniques for further evaluation.

Each of the RBSID events was associated with one of the primary hazards. To consider both frequency and severity of resulting accidents or service interruptions, a simplified risk analysis approach was used. This analysis identified the primary hazards most likely to result in the greatest loss to the industry. Potential effects of various mitigation measures for the hazards resulting in the greatest estimated loss were explored. CBAs were carried out for those mitigations likely to have the greatest effect.

6.1 Ranking of Primary Hazards by Frequency

Figure 3 shows a breakdown of all bridge-related service interruptions or accidents in the RBSID by the related primary hazard. There are a total of 8,740 events. The largest number of events (49 percent) is due to bridge strikes from highway traffic. Service interruptions related to moveable bridge signals comprise 35 percent of the database. The remaining 16 percent of the events are related to other causes. Although events related to bridge strikes and moveable bridge signals are clearly very common, they are often low-consequence events, with little or no damage to the bridge or equipment.

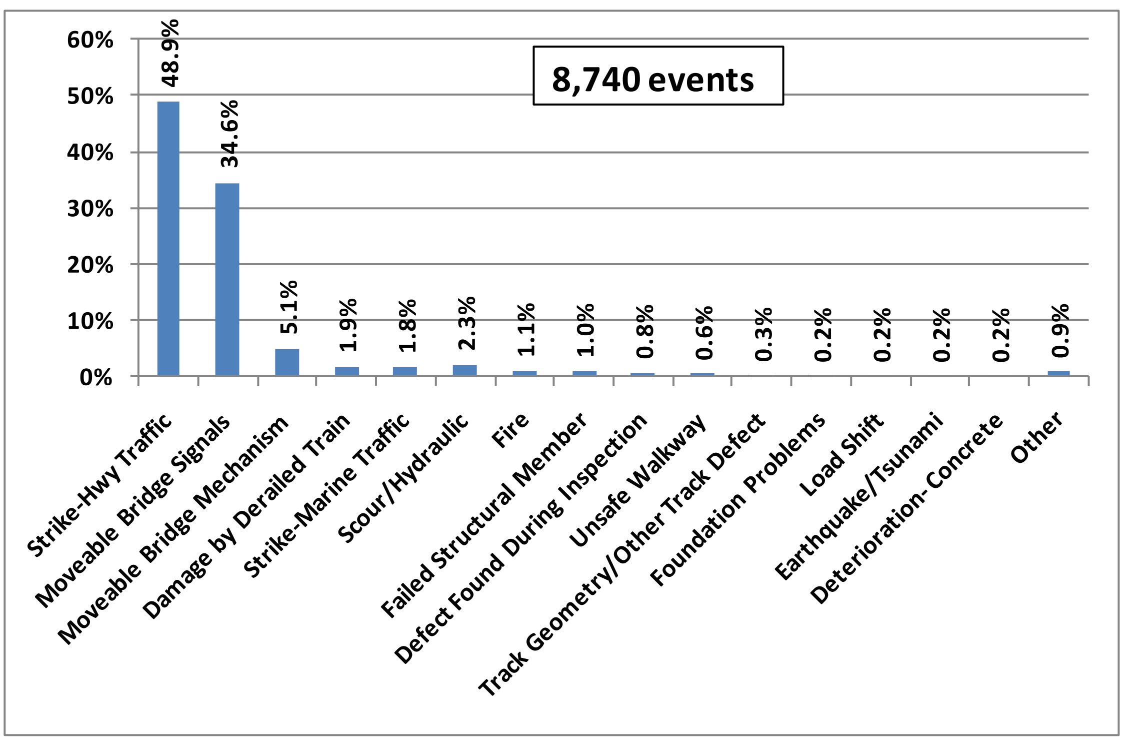

Figure 3. Frequency of Industry Bridge-Related Service Interruptions

Figure 4 shows the bridge failures in the RBSID from 1999 to 2010. For this comparison, a bridge failure is considered a total or partial collapse of a bridge. There were 29 bridge failures over the 11 years. Hydraulic problems (64 percent), foundation problems (17 percent), and failed structural members (17 percent) were the most common causes of bridge failures.

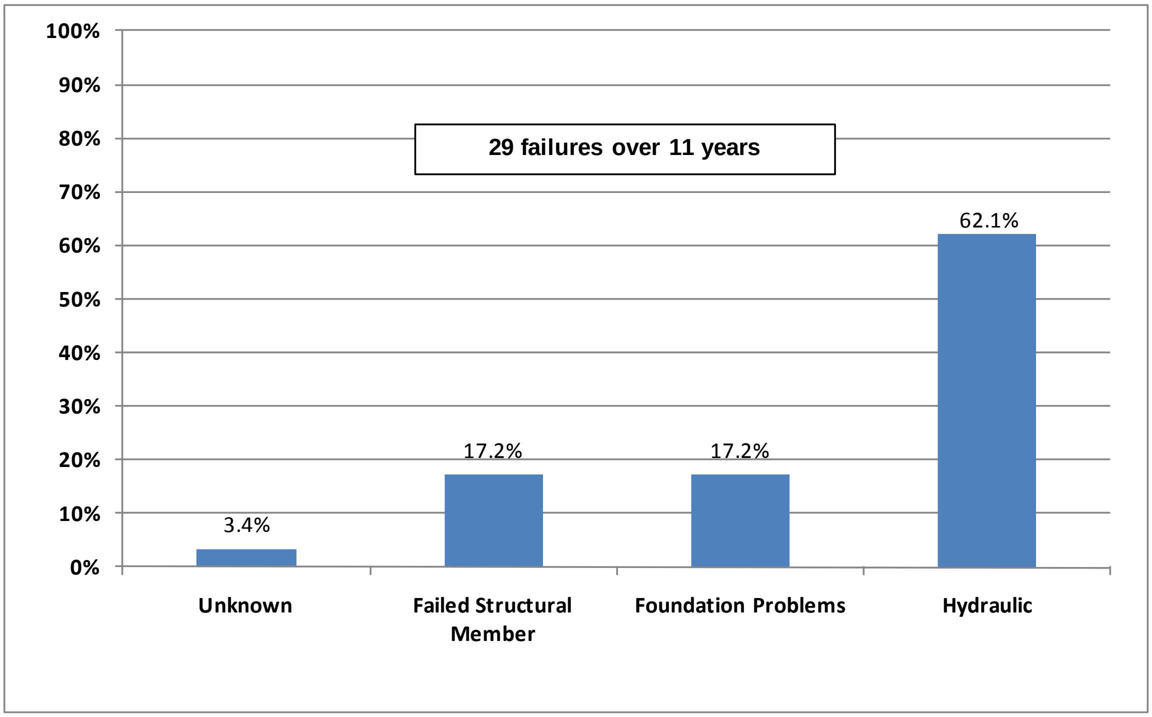

Figure 4. Frequency of Railroad Bridge Failures

For comparison, Figure 5 shows the causes of highway bridge failures in the United States from 1966 to 2005 (39). A similar percentage (60 percent) was due to hydraulic conditions, with marine collisions second at 12 percent.

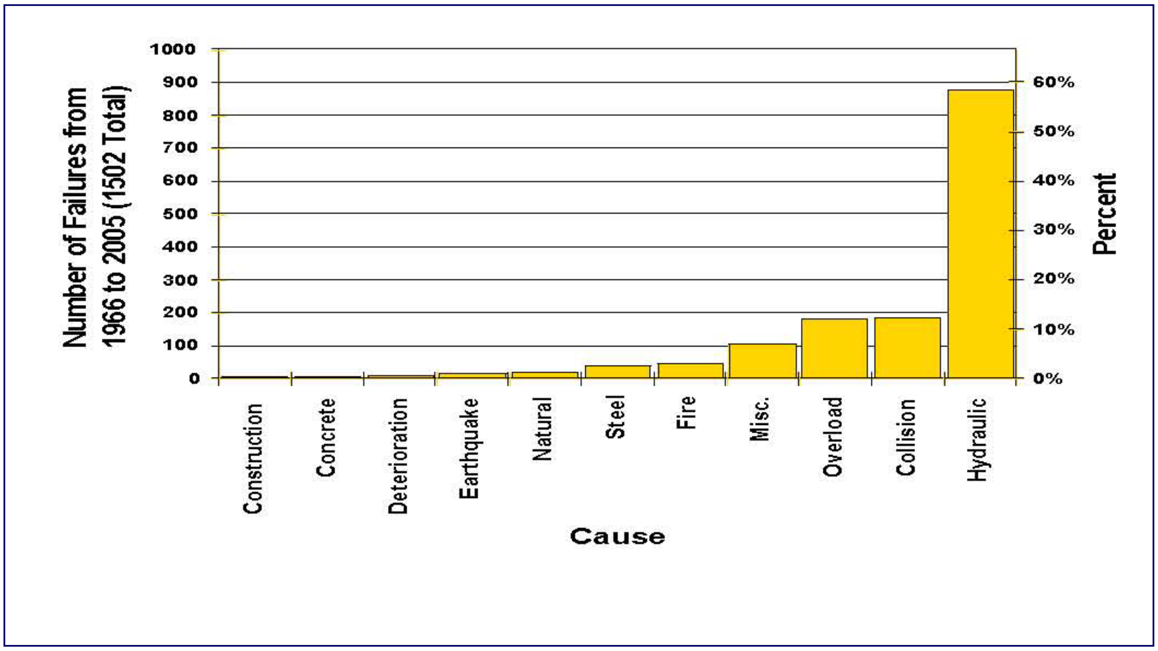

Figure 5. Highway Bridge Failures in United States from 1966 to 2005 (presented by Briaud – Texas Transportation Institute[39])

6.2 Events Resulting in Train Accidents

Events in which a train accident occurs because of a bridge problem represent 5 percent of the service interruptions listed in the RBSID.

6.3 Damage from External Means

It may be useful to separate bridge service interruptions or accidents into those caused by bridge deficiencies and those caused by external means. An example of a service interruption caused by a bridge deficiency is a condition found during an inspection. Trains may be delayed until appropriate action is taken. A common example of a service interruption caused by external means is a delay resulting from a bridge strike by a highway vehicle.

The RBSID includes 73 bridges that either failed because of bridge deficiencies or were destroyed by external means. Figure 6 shows that more than half of the failures were due to external means.

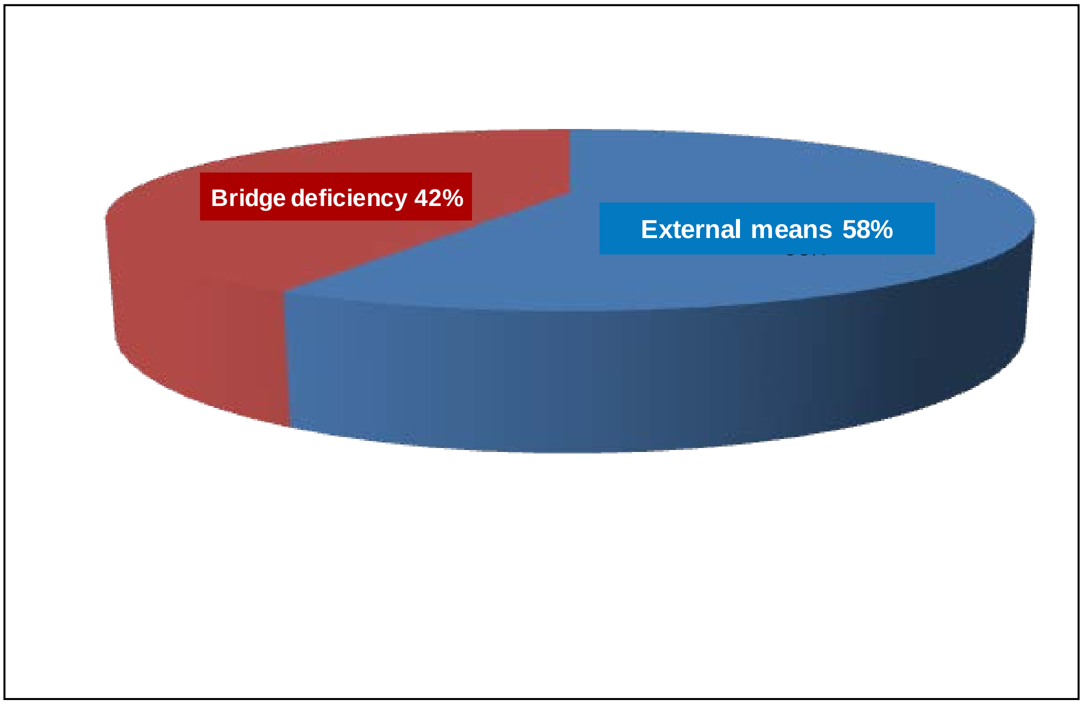

Figure 6. Percentage of Failures because of Bridge Deficiencies and External Means

6.4 Annual Risk Exposure

TTCI developed a simplified model to calculate a risk exposure ranking for each of the identified primary hazards. The simplified risk model considers both frequency and severity of loss. Each event in the RBSID was assigned a loss value. Next, these values were summed for each primary hazard and annualized. Then, the primary hazards were ranked. The hazards with the highest exposure were considered as a set of hazards to be considered for bridge monitoring.

6.4.1 Risk Exposure

Actual damage values were available for all of the events from the FRA database. These values were modified in several ways:

- First, they were factored for inflation based on the AAR Railroad Cost Recovery Index (40).
- A multiplier of 1.74 was applied to account for indirect damage. This multiplier was developed by AAR to account for clearing wreckage from the track, commodity loss and commodity damage. This multiplier is updated each year by TTCI as part of the AAR Strategic Research Initiatives Program. It is recognized that this average value does not account for all possibilities, but it is a first-level attempt to account for these costs. Total values are somewhat understated because the multiplier does not include cost of delays, traffic diversion, or business loss.
- Finally, the economic values of a statistical life and injury were accounted for based on guidance from the U.S. Department of Transportation (41).

Most of the information provided by the railroads did not include costs. Where actual damages were not available, general estimates were established.

6.4.2 Estimate of Loss

Each event was assigned a severity category from 1 to 4. Typically, these types of analyses use more categories, but the available detail in the RBSID does not justify further refinement.

- Category 1 events are the least serious. They are characterized by negligible damage with minor service interruption. A frequent example is a bridge strike in which traffic is delayed only until an inspection is conducted, and the inspection reveals marginal damage.
- Category 2 events result in major damage to the bridge and/or train. Generally, there are no injuries, however; significant service interruption occurs.
- Category 3 events are characterized by destruction or collapse of the bridge. These include bridge washouts, fires, and severe bridge strikes. There may be injuries involved.
- Category 4 events are the most serious, with both destruction of a bridge and severe damage to or loss of a train. There may be injuries and/or fatalities.

An estimate of loss was established for each of the categories. The estimate was based on extrapolation of available loss data and input from the industry TAG. A loss of $10,000 per event was established for Category 1 events based on the necessity of mobilizing a team to inspect and/or make minor repairs and any associated delay costs. Actual damage values were available for all of the Category 4 events.

Categories 2 and 3 events included a wide range of events with widely varying losses. For these, order of magnitude estimates were established by averaging available damage values for similar events in the FRA database. Estimated losses of $300,000 and $1,500,000 were established for Categories 2 and 3 events, respectively; Table 4 shows the basis for the loss values assigned to Categories 2 and 3 events.

Table 4. Basis for Assigned Loss Values

Severity	Average FRA Data	Median FRA Data	Estimated Loss per Event
2	$447,000	$157,500	$300,000
3	$1,806,900	$1,224,200	$1,500,000

Table 5 presents a summary of the category descriptions and costs. Because of the large number and limited details associated with the events, there were often overlaps. The authors applied the category descriptions in a general way and used judgment as necessary to classify each of the events. Severity 1 was assumed if the extent of damage or injuries was not available.

Table 5. Description of Severity Categories

Severity	Description	Examples	Loss Estimate
1	Minor service interruption; negligible damage.	• Bridge strike – inspection reveals negligible damage • Moveable bridge problems because of signal indication	$10,000
2	Major damage to bridge or train (significant service interruption). Generally, no injuries.	• Train derails and damages bridge • Bridge strike requiring repairs • Defect noted during periodic bridge inspection requiring extensive repairs	$300,000
3	Bridge collapses or is totally destroyed. There may be injuries.	• Bridge washed out • Bridge destroyed by fire • Severe bridge strike requiring bridge replacement	$1,500,000
4	Bridge destroyed with severe train damage or loss of train; there may be injuries and/or fatalities.	• Bridge collapses because of scour damage. Train travelling over bridge falls in	From FRA Safety Database

Table 6 breaks out the source of service interruption data by Severity Category.

Table 6. Source of Service Interruption Data by Category

Source	Category 1	Category 2	Category 3	Category 4	Total
FRA Database	1	126	20	30	177
Railroads	8,047	494	22	0	8,563
Total	8,048	620	42	30	8,740

6.4.3 Correction for Missing Data

To present loss estimates on a national basis, a correction factor was established to account for missing data. Reasons for missing data include:

- Some U.S. railroads chose not to participate in the investigation
- Some of the participating railroads only provided partial data
- The bridges of one participating railroad are mainly in Canada

The correction factor was based on the total number of railroad bridges in North America and their distribution by railroad.[1] An estimate of the number of the Canadian railroad's bridges in the United States was based on the distribution of their track miles between the United States and Canada.

There are a total of about 62,000 Class 1 railroad bridges in the United States. On the basis of railroad participation, TTCI estimates that the RSIBD contains data for about 32,000 of these bridges. This includes the U.S. portions of the participating Canadian railroad.

The remaining portion of the Canadian railroad's data was used to replace a portion of the missing U.S. data. This increased the total number of bridges represented to about 36,000. This total represents about 60 percent of the total number of U.S. bridges.

On the basis of this rough estimate, all estimates of loss were factored to correct for the missing 40 percent of the data.

6.5 Annual Risk Exposure

Risk exposure values for each event are presented as annual risk. For the FRA data from 1999 to 2010, the risk exposure was annualized over 11 years. For the railroad data, an appropriate period was chosen based on the period for which data were reported.

The RBSID shows that high-consequence events such as the Big Bayou Canot or Kingman, AZ, accidents have been very infrequent. None of these events occurred from 1999 through March 2010. A query over the last 30 years revealed only four of these high-consequence accidents. When the annual risk exposure was compiled, these events were included with their cost annualized over a 30-year period.

This simplified approach has several drawbacks. The last high-consequence accident was the Kingman Arizona accident in 1997. It may indicate that improved procedures put in place by railroads and other entities have reduced the risk. A comprehensive analysis of potential high-consequence events would need to consider not only historical events but also potential events. Although methods exist for such an analysis, it is beyond the scope this report.

6.5.1 Ranking of Primary Hazards by Risk Exposure

Figure 7 shows the ranking of primary hazards by annual risk exposure based on the historical data assembled. The highest exposure is $25.8 million from *Scour/Hydraulic*. This is largely driven by the 1997 Amtrak derailment in Kingman, AZ. Next in rank is *Strike—Marine Traffic*. This is largely driven by the 1993 Amtrak accident on the Big Bayou Canot Bridge near Mobile, AL.

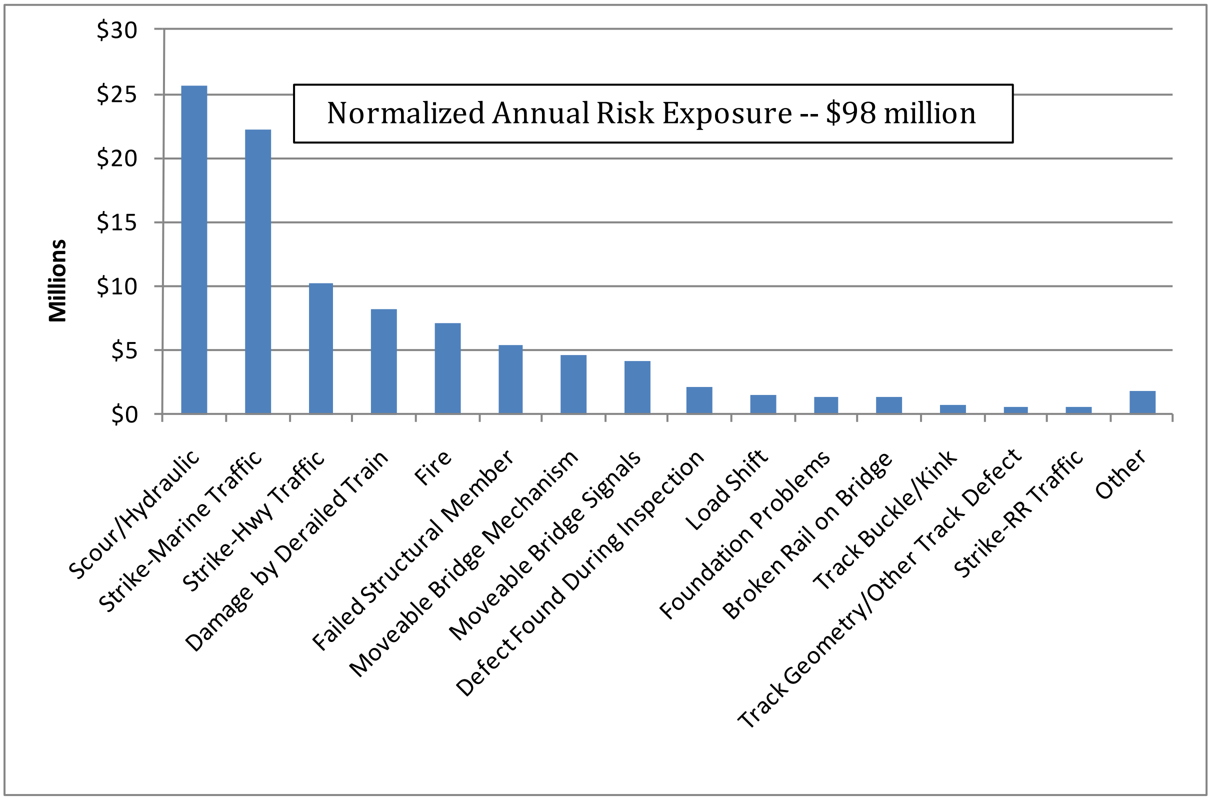

Figure 7. Ranking of Primary Hazards by Annual Risk – All Data

Figure 8 shows the ranking of primary hazards by annual risk exposure from 1999 to 2010 only. Based on this period, the annual risk is only $72 million. The highest exposure is still from *Scour/Hydraulic*, followed by *Strike—Highway Traffic* and *Damage by Derailed Train*. Over 25 percent of the $98 million from Figure 7 is from the four significant accidents that occurred between 1982 and 1997.

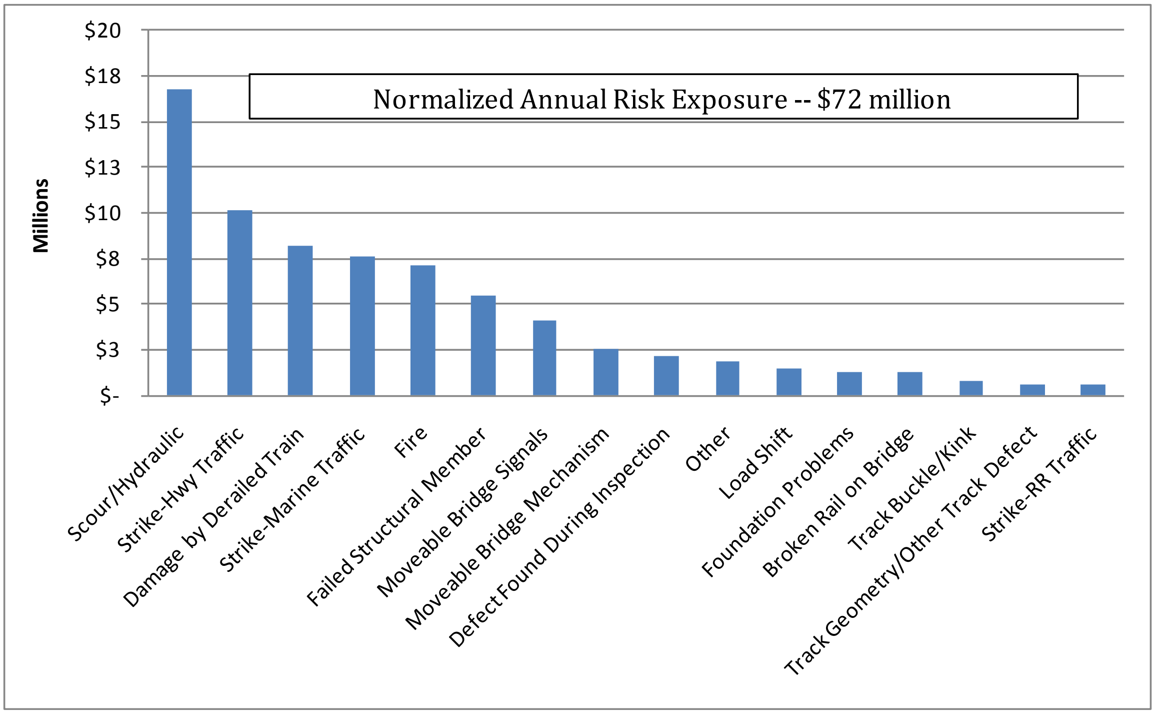

Figure 8. Ranking of Primary Hazards by Annual Risk – 1999-2010 Data

6.6 Risk Control Matrix

A risk control matrix was developed to match potential problems with existing control measures and to identify those areas where additional controls may be warranted. Figure 9 is an excerpt from the matrix. Appendix B has the entire matrix.

	Protection						Scheduled Inspections							Existing Detection Systems									Advanced / Prospective Mitiagation Techniques											
Description of Loss	Highway Signs, Flashing Lights, Paint, etc	Bridge Lighting	Bridge Shielding (Fender systems, collision beams)	Inner Guard Rail	Truss Guard Rails	Collision Posts (trusses)	Annual and Special Inspection (bridge insp)	Track Inspector	Moveable bridge Inspection	Moveable Bridge Tender / Remote Bridge Operator	NDT	Underwater Inspection	Automated Track Inspe Vehicle	Inspection by others	High Water Detector	Weather Notification Network	High/Wide Load or Shifted Load Detector	Dragging Equipment Detector	Overload/imbalanced Load Detector (OILD)	Signal System	Rail Strain Measurement	Track Displacement Detector	Bridge Strike Detector	Mid Span Displacement	Self Diagnostic Moveable Bridges	Unattended Scour Monitoring	Remote Underwater Inspection	Bridge Presence Indication	Strain measurement	Tilt monitors	Fire Detection System	Fireproofing	Vehicle Borne Monitoring	Pile Displacement Detector
Bridge Strike-Highway Vehicle																																		
Train Accident Due to Undetected Collapse	X	X	X					X						X						O			X					X		O				
Repair or Replacement of Collapsed Bridge	X	X	X																															
Train Derails due to Undetected Damage or Misalignment	X	X	X	X				X						X								X	X											
Repair costs -- Bridge Misalignment/Movement	X	X	X																															
Repair Costs -- Damage to Substructure/Superstructure	X	X	X																															
Inspection costs -- no damage	x	X	X																															
Derailed Train																																		
Repair or Replacement of Collapsed Bridge				X	X	X								X			X	X																
Repair Costs -- Damage to Substructure/Superstructure				X	X	X								X			X	X																
Scour																																		
Train Accident Due to Undetected Collapse							x	x				X	o	X	X	X				O		o		x		X	X	X		O				X
Repair or Replacement of Collapsed Bridge							x					X												x		x	X							X
Train Derails due to Undetected Damage or Misalignment				X	X	X	x	X				x	o	X	X	X						X		x		X	x						O	X
Repair costs -- Bridge Misalignment/Movement							x					X												x		X	X						O	X
Repair Costs -- Damage to Substructure/Superstructure							x					X												x		x	x						o	X
Bridge Washout																																		
Train Accident Due to Undetected Collapse								X						X	X	X				O		o						X		O				
Repair or Replacement of Collapsed Bridge																																		
Train Derails due to Undetected Damage or Misalignment				X	X	X		X						X	X	X						X											O	

Figure 9. Excerpt from Risk Control Matrix

6.6.1 Primary Hazards

The left column of the matrix lists the primary hazards estimated to have the highest risk exposure and the type of loss that would likely result. Potential mitigation techniques or control measures are listed in the top row of the matrix. If a control measure is likely to mitigate the loss, a mark is put in the cell matching the control measure with the potential loss. An "X" is used to indicate a probable match and an "O" is used to indicate a possible match. This process provides a quick indication of which types of losses are without controls and which control measures will apply to the greatest number of losses.

The 15 primary hazards with the highest risk exposure from Figure 7 are included in the risk control matrix. Several potential loss scenarios are associated with each of the primary hazards. Loss scenarios can range from inspection costs only resulting from a bridge strike to a worst-case event such as a train accident caused by an undetected bridge collapse. These loss scenarios were generalized into the 15 potential losses listed in Table 7. The appropriate loss scenarios are included in the left column of the risk control matrix with the appropriate primary hazard.

Table 7. Potential Losses Due to Primary Hazards

Potential Loss	Comments
Train accident caused by undetected collapse	Low-frequency/high-consequence—both the bridge and the train lost
Train accident caused by incorrect indication of closed bridge	
Repair or replacement of collapsed bridge	
Train derails due to undetected damage or misalignment	
Repair costs — bridge misalignment/movement	
Repair costs — damage to bridge substructure/superstructure	
Inspection costs — no damage	High-frequency/low-consequence
Repairs/delays associated with incorrect indication of closed bridge	
Repairs/delays because of unidentified track occupancy	Result of signal system problems
Repairs delays caused by incorrect indication of open bridge	
Train derails caused by train collision with bridge	
Repair costs — damage to moveable bridge because of incorrect operation	
Train derails because of track defect	
Track repair costs	
Repair/delay costs—not able to open/close bridge	

6.6.2 Mitigation Techniques

The list of potential mitigation techniques was developed based on consultation with the industry TAG. Many of these are described in Section 3. This list may not be comprehensive but represents those measures most likely to be considered for implementation. The measures were separated into four categories: Bridge Protection Systems, Scheduled Inspections, Existing Detection Systems, and Advanced or Prospective Mitigation Techniques

Tables 8–11 list the control measures selected for evaluation from each of the categories.

Table 8. Bridge Protection Systems

Bridge Protection Systems
Highway Signs, Flashing Lights, Paint, etc.
Bridge Lighting
Bridge Shielding (Fender systems, collision beams)
Inner Guard Rail
Truss Guard Rails
Collision Posts (trusses)

Table 9. Scheduled Inspections

Scheduled Inspection
Annual and Special Inspection
Inspection by Track Inspector
Moveable Bridge Inspection
Moveable Bridge Tender/Remote Bridge Operator
NDE
Underwater Inspection
Automated Track Inspection Vehicle

Table 10. Existing Detection Systems

Detection System
Inspection by others
High-Water Detector
Weather Notification Network
High/Wide Load or Shifted Load Detector
Dragging Equipment Detector
Weigh-In-Motion for Overloaded Cars/Trucks
Signal System
Rail Strain Measurement
Track Displacement Detector

Table 11. Advanced/Prospective Mitigation Techniques

Mitigation Techniques
Bridge Strike Detector
Midspan Displacement
Self-Diagnostic Moveable Bridges
Unattended Scour Monitoring
Remote Underwater Inspection
Bridge Presence Indication
Strain Measurement
Tilt Monitors
Fire Detection System
Fireproofing
Vehicle Borne Monitoring
Pile Displacement Detector

6.6.3 Risk Control Matrix Summary

Figure 10 shows a summary of the risk control matrix results. The bars indicate the number of times an occurrence matched a potential loss. A number of conclusions can be drawn:

- Bridge inspection (including annual and special inspection, inspection by track inspectors, and inspection by others) is an effective control for many potential losses. Currently, inspection is the first line of defense for the railroads.
- There is a large opportunity for defects to be detected by others working on the railway. It may indicate that training these individuals to recognize bridge defects may be a cost-effective way of reducing losses from bridge accidents and service interruptions.
- Protection systems, where they can be implemented, are likely more effective than monitoring.
- Track displacement detectors, tilt monitors, and midspan displacement monitors should be considered for additional investigation.

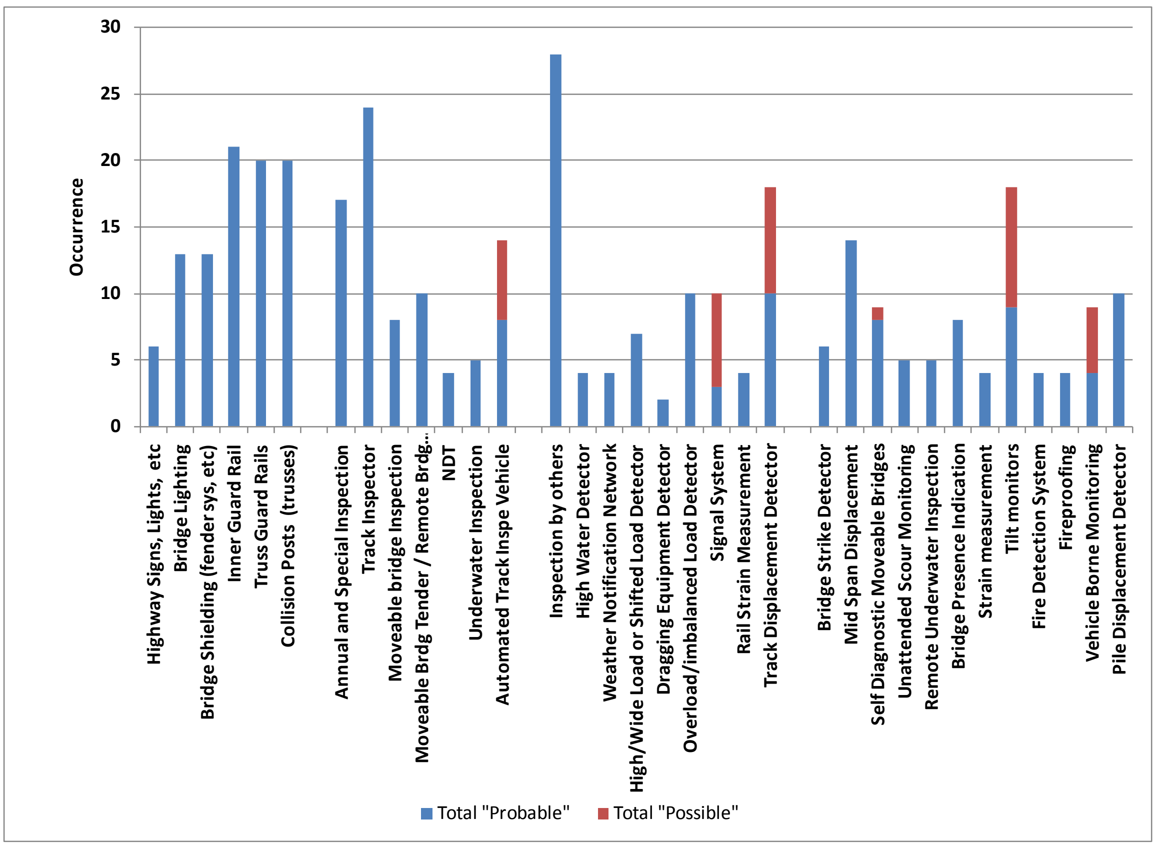

Figure 10. Risk Control Matrix Summary

7. Economic Analysis

The estimates of risk exposure developed in Section 6 were used for a preliminary economic analysis for 15 potential monitoring systems. First, the database was queried for the bridge events that could potentially be mitigated by each potential monitoring system. Actual or estimated costs were tallied. The total cost for each system was considered an upper limit of the preventable annual risk exposure that the monitoring system might mitigate. Discounted cashflow techniques were used on selected monitoring systems to estimate the break-even point for each system.

7.1 Upper Limit of Preventable Annual Risk Exposure

The RBSID was queried for the bridge events that could possibly be mitigated by each potential monitoring system. Then the risk exposure for each identified event was considered to estimate how much might be mitigated by the potential system. Where actual values were available, any injuries or fatalities as well as any property damage that was related to equipment and track were included. That is because, in general, the monitoring system would not stop damage to the bridge but only the loss from the resulting accident. Where losses were estimated, the entire amount was used.

Appendix C includes details for each of the systems considered.

Figure 11 displays the results of the review. Of the 15 monitoring systems considered, seven had estimated upper limits between $13.6 and $35.2 million. The remaining eight systems had estimated annual upper limits $5.1 million or less. On the basis of these results, the top seven monitoring systems were selected for additional evaluation. The selected systems are:

- Track Displacement Detector
- Bridge Strike Detector
- High-Water Detector
- Unattended Scour Monitoring
- Tilt Monitors
- Foundation Displacement Detector
- Weather Notification Network

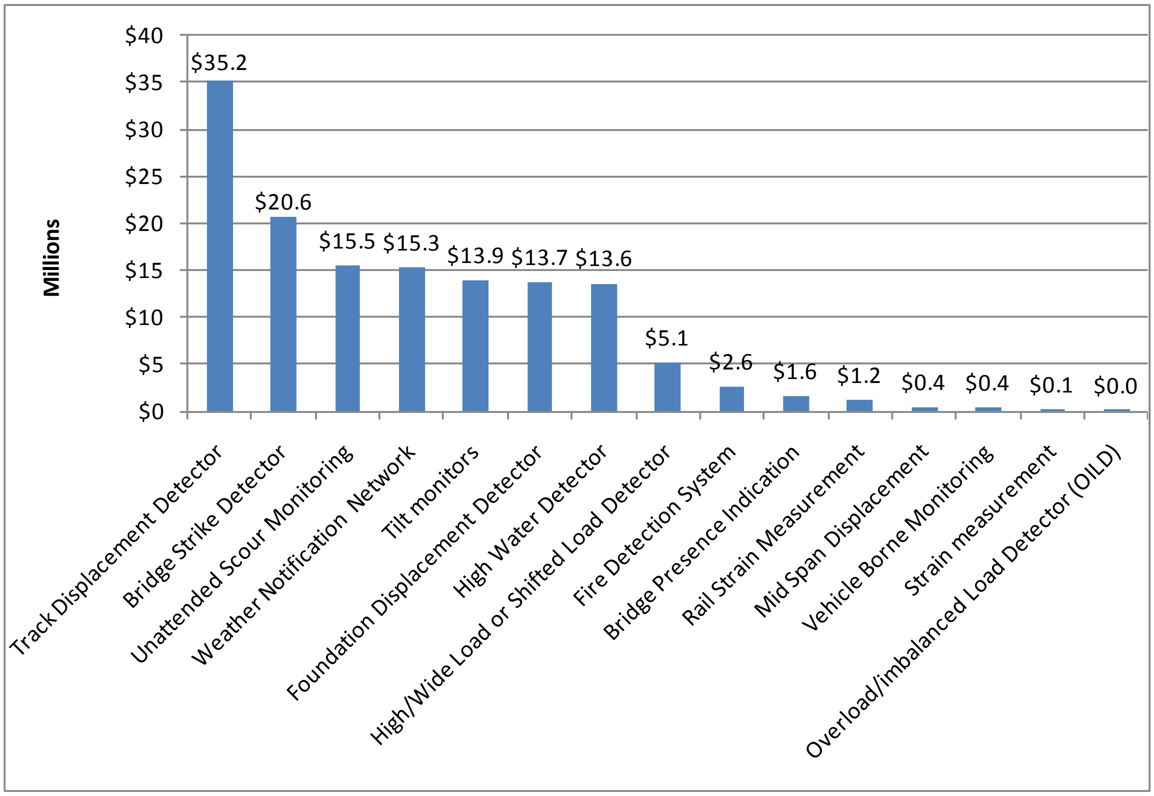

Figure 11. Potential Preventable Annual Risk Exposure by Technology

The selected monitoring systems included track displacement detectors and tilt monitors, which were identified in the risk control matrix as potentially effective mitigation techniques. The midspan displacement detector was also identified in the risk control matrix as a potentially effective system. However, because estimated preventable annual risk exposure was only $0.4 million, it was not selected for further analysis.

7.2 CBA of Selected Monitoring Systems

A discounted cashflow CBA was conducted on six of the seven selected potential monitoring systems.

Although benefits of subscribing to a weather notification system are likely to be substantial, detailed analysis is beyond the scope of this investigation. Considerations include:

- Benefits are shared across the entire railroad system.
- Notification of a potentially hazardous condition is not sufficient to prevent a problem. Additional action is required, such as sending inspectors to the affected areas.

For the remaining systems, the analysis considered the maximum amount per bridge that could be spent on a system. The amount spent could not be greater than the preventable annual risk exposure. This can be expressed as follows:

$$R_a \geq M_c$$

$$M_c = f\left(i_c, e, fp, m_c, o_c, u_c, c_c\right)$$

Where

R_a = preventable annual risk exposure

M_c = risk mitigation costs

i_c = initial cost to include purchase and installation

e = device effectiveness

$f\,p$= false positive and reliability issues

m_c = maintenance costs

o_c = operational costs to include data analysis, communications, etc.

u_c = upgrade costs

c_c = cost of capital

7.3 Assumptions and Estimations

The following assumptions and estimations were used:

- Because device effectiveness is not known, a parametric approach was used with effectiveness considered at 10, 30, 50, and 75 percent.
- TTCI's experience with deployment of the Trackside Acoustic Detection System (TADS®) was used for a number of estimates.
  - A false-positive rate of 3 percent of the number of service interruptions was used. It was assumed that the cost of a false positive would be the same as a severity Category 1 event of $10,000.
  - The initial cost would need to include purchase of the product, installation costs, and other associated railroad costs including adding power and communication lines.
  - Annual maintenance costs and operation costs combined are estimated at 1 percent of the installation cost.
  - Upgrades are done every 5 years and are 15 percent of the installation cost. (Track displacement detector is not upgraded.)
  - Life of the detector is 15 years. (Track displacement detector life is 10 years with no upgrades at a replacement cost of 50 percent of initial installation.)

The break-even amount was estimated based on a 15-year net present value analysis. A discount rate of 11.9 percent was used. This is the rate currently used by AAR and includes allowance for inflation.

7.4 Summary of Economic Analysis

The maximum cost per bridge for each implemented technology is highly dependent on the effectiveness of the technology, which refers to the percent of the problem that will be prevented. For this preliminary analysis, results are presented for 10, 30, 50, and 75 percent effectiveness.

Figure 12 shows the maximum cost per bridge to break even for each of the selected bridge monitoring systems. This preliminary analysis assumes that the monitoring system is installed on all of the bridges. The track displacement detector has the most promising result. At 50 percent effectiveness, about $1,600 could be spent per bridge. At 75-percent effectiveness, about $2,400 could be spent per bridge. Either the technology would have to be very inexpensive or a targeted approach is required.

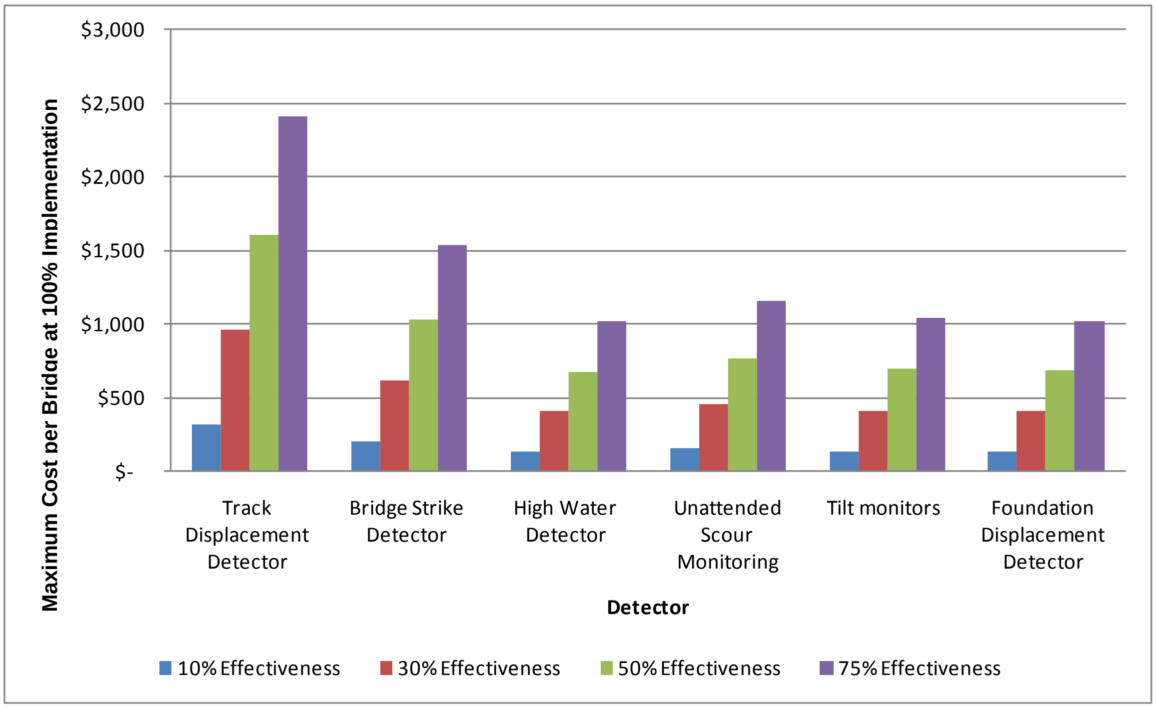

Figure 12. Maximum Cost per Bridge for Technology to Break even

A large percentage of the Track Displacement detector's value would be in the reduction of risk of derailment resulting from a bridge strike-induced misalignment. In this case, selective installation to protect the most vulnerable bridges may be advantageous. Bridges most vulnerable to strikes could be identified based on location and history.

As an example, two cases of selective installation are considered. The first case assumes that track displacement detectors are fitted on 10 percent of bridges. The second assumes that detectors are installed on 25 percent of the bridges. Greater protection may be necessary on some lines because of traffic density and difficult operating environment.

Figure 13 shows maximum cost per bridge for each case, with assumed effectiveness ranging from 10 to 75 percent. Assuming that the annual risk is reduced by 50 percent, the maximum cost available per bridge would be increased from the $1,600, shown in Figure 12 for installation on 100 percent of bridges, to $6,400 if the percentage of installations could be reduced to 25 percent, and to $24,000 if the percentage of installations could be reduced to 10 percent.

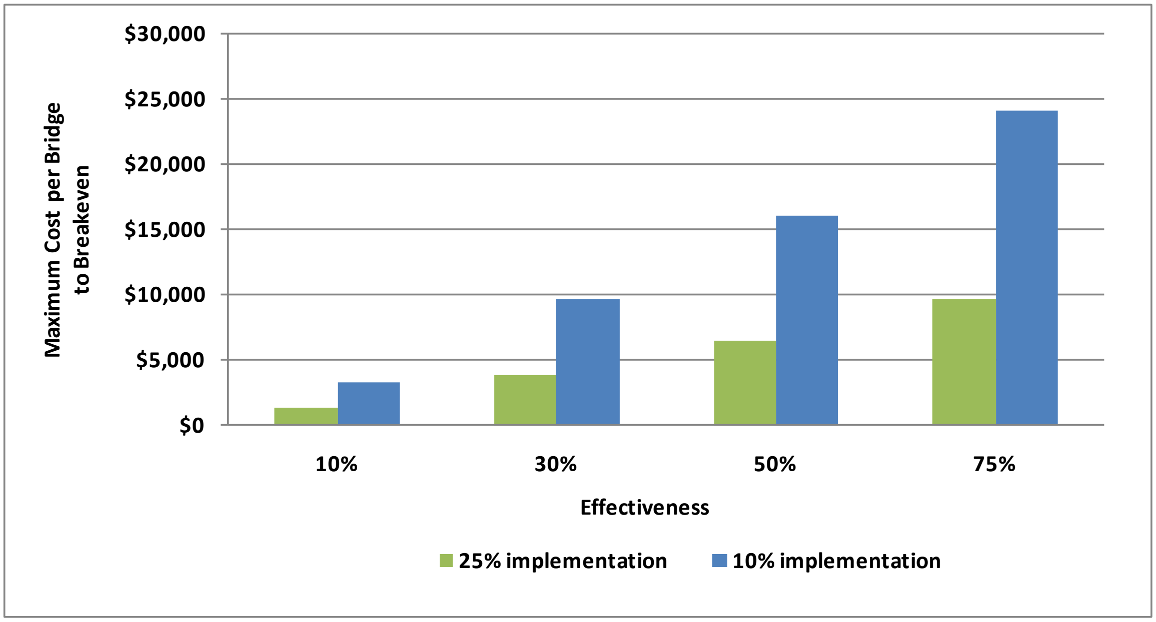

Figure 13. Maximum per Bridge Cost of Track Displacement Detector if Installed on 10 or 25 Percent of Bridges

8. Summary

This project was pursued to develop an understanding of the types of bridge problems that cause accidents or service interruptions and to use this information to evaluate the need to develop new bridge monitoring systems. Existing monitoring systems and other mitigation techniques were also considered, so that efforts can be focused on areas of greatest need.

A literature review was carried out to identify existing and potential monitoring systems and to identify similar work that has been undertaken. An industry TAG was formed consisting of chief railroad bridge engineers, Volpe, and FRA to provide feedback and direction in the project. The TAG was periodically asked to comment on results and to review key assumptions used in the study.

Data were gathered from the FRA Safety Database, from railroad databases where available, and from interviews with industry experts. Although the FRA Safety Database identifies bridge failures, the cause codes do not focus narrowly enough to understand what underlying causes are involved. Further, only events above a damage cost threshold and involving train operation are included. Unlike the FRA data, railroad data include major events that do not involve train operations, such as bridge fires and bridge washouts. In addition, many less serious but frequent events are included. However, the railroad data collected varied widely from railroad to railroad. Some railroads provided a detailed description of each service delay including the delay time, whereas others provided input based on the recollection of key personnel. Both FRA Safety Database and railroad data lack detail. Little railroad data older than 10 years is available.

Data from various sources were unified and collated into a useful form in the RBSID. The RBSID contains over 8,700 records, including derailments from the FRA Safety Database and service interruptions information provided by the five railroads. The database is in Microsoft Access to allow for easy entry and query.

Using the available information, a preliminary ranking of hazards based on frequency and severity of resulting accidents of service interruptions was carried out.

Bridge strikes from highway vehicles and problems relating to moveable bridge signals comprise the largest number of accidents and service interruptions. Because these are generally low-consequence events, they may not represent the problems with the largest effect on industry safety. Table 12 shows the 15 most frequent hazards.

Table 12. Top 15 Primary Hazards by Frequency

Primary Hazard	Percentage
Strike-Hwy Traffic	48.9%
Moveable Bridge Signals	34.6%
Moveable Bridge Mechanism	5.1%
Damage by Derailed Train	1.9%
Strike-Marine Traffic	1.8%
Scour/Hydraulic	2.3%
Fire	1.1%
Failed Structural Member	1.0%
Defect Found during Inspection	0.8%
Unsafe Walkway	0.6%
Track Geometry/Other Track Defect	0.3%
Foundation Problems	0.2%
Load Shift	0.2%
Earthquake/Tsunami	0.2%
Deterioration- Concrete	0.2%

An analysis that considers both frequency and severity of the events estimates that the annual risk exposure from bridge problems is about $98 million. The largest contributor is scour combined with other bridge hydraulic problems at about $26 million per year. This is largely driven by the 1997 Kingman, AZ, bridge accident. Next in rank is strike from marine traffic at about $23 million per year, which is largely driven by the 1993 Bayou Canot accident. Damage by derailed trains, fire, and failed structural members follows. Over 25 percent of the $98 million is attributable to four significant accidents that occurred between 1982 and 1997. Table 13 summarizes the ranking of hazards by annual risk exposure.

Table 13. Summary of Annual Risk Exposure

Primary Hazard	Annual Risk Exposure (millions)
Scour/Hydraulic	$ 25.6
Strike-Marine Traffic	$ 22.1
Strike-Hwy Traffic	$ 10.2
Damage by Derailed Train	$ 8.2
Fire	$ 7.2
Failed Structural Member	$ 5.5
Moveable Bridge Mechanism	$ 4.7
Moveable Bridge Signals	$ 4.1
Defect Found during Inspection	$ 2.2
Load Shift	$ 1.5
Foundation Problems	$ 1.3
Broken Rail on Bridge	$ 1.3
Track Buckle/Kink	$ 0.8
Track Geometry/Other Track Defect	$ 0.6
Strike-RR Traffic	$ 0.6
Other	$ 1.9
Total	**$ 97.5**

A risk control matrix was developed to match potential problems with existing control measures and to identify those areas where additional controls may be warranted. Results suggest that:

- Protection systems are likely more effective than monitoring.
- Bridge inspection is an effective control for many potential losses. It is the first line of defense for the railroads.
- There is a large opportunity for defects to be detected by others working on the railway, indicating that training for recognition of bridge defects may be a cost-effective way of reducing losses from bridge accidents and service interruptions.
- Track displacement detectors, tilt monitors, and midspan displacement monitors should be considered for additional investigation.

The estimates of risk exposure were used for a preliminary economic analysis of 15 potential monitoring systems. First, the database was queried for the bridge events that could possibly be mitigated by each potential monitoring system. Actual or estimated costs were tallied.

Discounted cashflow techniques were used on selected monitoring systems to estimate the break-even point for each system.

Of the 15 monitoring systems considered, 7 had estimated annual upper limits of preventable annual risk exposure between about $24.8 and $9.6 million. The remaining eight systems had estimated annual upper limits about $5 million or less. On the basis of these results, the top seven monitoring systems were selected for additional evaluation. The selected systems were:

- Track Displacement Detector
- Bridge Strike Detector
- HighWater Detector
- Unattended Scour Monitoring
- Tilt Monitors
- Foundation Displacement Detector
- Weather Notification Network

A discounted cashflow CBA was conducted on six of the seven selected potential monitoring systems. The CBA considered the maximum initial cost per bridge that could be spent on a system based on the preventable annual risk exposure. Results indicate that for implementation of any of the systems to be cost-effective, a selective implementation strategy would be required. Across-the-board implementation would not be cost-effective. Additional work is recommended to design a structured, risk-based approach for selective implementation of monitoring systems.

9. Recommendations

Results have indicated that the annual risk exposure from bridge related events is nearly $100 million. Preventable annual risk exposure over $36 million could be attributed to certain detectors. However, because of the large number of railroad bridges in service, results indicate that for implementation of any of the systems to be cost-effective, a selective implementation strategy would be required. Across-the-board implementation would not be economical.

A second phase of work is a proposed development of a risk assessment method to identify those bridges that will give the best return for having remote monitors installed. A comprehensive analysis of potential high-consequence events would need to include development of a structured approach to consider the possibility of events that have not been documented historically. The work would likely require one or more moderated meetings of experts to evaluate potential bridge-related problems that may represent risks to personnel or equipment. A deliverable for this work could include a computer program to help bridge owners determine which of their bridges should be considered for monitoring.

The literature review and the analyses reported here indicate that good bridge inspections are the first and last line of defense against bridge failures. Service interruptions due to defects found during inspections accounted for over $2 million in annual risk exposure. This indicates that scheduled inspections are identifying problems before they cause operational problems. Because inspections are an integral and successful part of maintaining bridge safety and reliability, additional work is proposed to identify technologies that can aid the inspection process. This might include improved NDE techniques of bridge health monitoring technologies.

Railroads would be surveyed to identify the types of problems that are being found during inspections. Bridge inspectors and other industry experts would be interviewed for an overview of needs to be addressed. Current and potential technologies would be identified.

An FHWA program to introduce new bridge inspection technologies is discussed in this report. The program identified a suite of five of the latest relatively inexpensive, portable, technician-driven NDE technologies to aid bridge inspectors. FHWA developed a one-day seminar to familiarize bridge inspectors with these technologies. The FHWA effort should be consulted for the applicability of the identified technologies for railroad applications and for the methods used to identify the five technologies. Deliverables for this work could include a short seminar similar to the one developed by the FHWA.

Railroads should consider development of training courses for track inspectors and others on identification of bridge hazards.

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Appendix A.
Risk Control Matrix

	Protection						Scheduled Inspections							Existing Detection Systems									Advanced / Prospective Mitiagation Techniques											
Description of Loss	Highway Signs, Lights, etc	Bridge Lighting	Bridge Shielding (fender sys, etc)	Inner Guard Rail	Truss Guard Rails	Collision Posts (trusses)	Annual and Special Inspection	Track Inspector	Moveable bridge Inspection	Moveable Brdg Tender / Remote Brdg Operator	NDT	Underwater Inspection	Automated Track Inspe Vehicle	Inspection by others	High Water Detector	Weather Notification Network	High/Wide Load or Shifted Load Detector	Dragging Equipment Detector	Overload/imbalanced Load Detector	Signal System	Rail Strain Measurement	Track Displacement Detector	Bridge Strike Detector	Mid Span Displacement	Self Diagnostic Moveable Bridges	Unattended Scour Monitoring	Remote Underwater Inspection	Bridge Presence Indication	Strain measurement	Tilt monitors	Fire Detection System	Fireproofing	Vehicle Borne Monitoring	Pile Displacement Detector
Bridge Strike-Highway Vehicle																																		
Train Accident Due to Undetected Collapse	X	X	X					X						X						O			X					X		O				
Repair or Replacement of Collapsed Bridge	X	X	X																															
Train Derails due to Undetected Damage or Misalignment	X	X	X	X				X						X								X	X											
Repair costs – Bridge Misalignment/Movement	X	X	X																															
Repair Costs -- Damage to Substructure/Superstructure	X	X	X																															
Inspection costs – no damage	x	X	X																															
Derailed Train																																		
Repair or Replacement of Collapsed Bridge				X	X	X								X			X	X																
Repair Costs -- Damage to Substructure/Superstructure				X	X	X								X			X	X																
Scour																																		
Train Accident Due to Undetected Collapse							x	x				X	o	X	X	X				O		o		x		X	X	X		O				X
Repair or Replacement of Collapsed Bridge							x					X												x		x	X							X
Train Derails due to Undetected Damage or Misalignment				X	X	X	x	X				x	o	X	X	X						X		x		X	x						O	X
Repair costs – Bridge Misalignment/Movement							x					X												x		X	X						O	X
Repair Costs -- Damage to Substructure/Superstructure							x					X												x		x	x						o	X
Bridge Washout																																		
Train Accident Due to Undetected Collapse								X						X	X	X				O		o						X		O				
Repair or Replacement of Collapsed Bridge																																		
Train Derails due to Undetected Damage or Misalignment				X	X	X		X						X	X	X						X											O	
Repair costs – Bridge Misalignment/Movement																																		
Repair Costs -- Damage to Substructure/Superstructure																																		
Fire																																		
Train Accident Due to Undetected Collapse								x						x						o		o						x		o	x	x		
Repair or Replacement of Collapsed Bridge																															x	x		
Train Derails due to Undetected Damage or Misalignment				x	x	x		x						x								o								o	x	x	o	
Repair Costs -- Damage to Substructure/Superstructure																															x	x		
Inspection costs – no damage																																		
Moveable Bridge Signals																																		
Train Accident due to Incorrect Indication of Closed Bridge									x	x															x									
Repairs/Delays associated with Incorrect indication of Closed Bridge									X	X															x									
Repairs / Delays due to Unidentified Track Occupancy									X	X															x									
Repairs Delays due to Incorrect Indication of Open Bridge									X	X															x									

X	=	probable match
O	=	possible match

Figure A1. Risk Control Matrix Page 1

	Protection						Scheduled Inspections							Existing Detection Systems									Advanced / Prospective Mitiagation Techniques											
Description of Loss	Highway Signs, Lights, etc	Bridge Lighting	Bridge Shielding (fender sys, etc)	Inner Guard Rail	Truss Guard Rails	Collision Posts (trusses)	Annual and Special Inspection	Track Inspector	Moveable bridge Inspection	Moveable Brdg Tender / Remote Brdg Operator	NDT	Underwater Inspection	Automated Track Inspe Vehicle	Inspection by others	High Water Detector	Weather Notification Network	High/Wide Load or Shifted Load Detector	Dragging Equipment Detector	Overload/imbalanced Load Detector	Signal System	Rail Strain Measurement	Track Displacement Detector	Bridge Strike Detector	Mid Span Displacement	Self Diagnostic Moveable Bridges	Unattended Scour Monitoring	Remote Underwater Inspection	Bridge Presence Indication	Strain measurement	Tilt monitors	Fire Detection System	Fireproofing	Vehicle Borne Monitoring	Pile Displacement Detector
Failed Structural Member																																		
Train Accident Due to Undetected Collapse							x	x			x		o	x					x	o		o		x				x	x	x			x	
Repair or Replacement of Collapsed Bridge							x				x								x					x					x	X			x	
Train Derails due to Undetected Damage or Misalignment							x	x			x		o	x					x			x		x					x	X			x	
Repair Costs -- Damage to Substructure/Superstructure							X				X								x					x					x	X			x	
Load Shift																																		
Train Accident Due to Undetected Collapse				x	x	x		x						x			x		x			o	X					X		O				
Repair or Replacement of Collapsed Bridge				x	x	x											X		x															
Train Derails due Collision with Bridge				x	x	x		x											x															
Train Derails due to Undetected Damage or Misalignment				X	x	x		x						x			x		x			x	X											
Repair Costs -- Damage to Substructure/Superstructure					X	x											X		x															
Inspection costs -- no damage																	x		x															
Moveable Bridge Mechanism																																		
Train Derails due to Undetected Damage or Misalignment								x	x	x				x											x					o				
Repair costs -- Bridge Misalignment/Movement									X	X															x					o				
Repair of Damage to Bridge Due to Incorrect Operation									X	X															x					o				
Repair / Delay Costs -- Not Able to Open/Close bridge									x	x															x									
Broken Rail on Bridge																																		
Repair or Replacement of Collapsed Bridge				X	x	x		x					x	x						x														
Repair Costs -- Damage to Substructure/Superstructure				X	x	x		x					x	x						x														
Train Derails due to Track Defect				x	x	x		x					x	x						x														
Repair Track													X																					
Bridge Strike-Marine Traffic																																		
Train Accident Due to Undetected Collapse		x	x					x		x				x						o		o	x		o			x						
Repair or Replacement of Collapsed Bridge		x	X																															
Train Derails due to Undetected Damage or Misalignment		x	x	X				x		x				x								x	x											
Repair costs -- Bridge Misalignment/Movement		x	X																															
Repair Costs -- Damage to Substructure/Superstructure		x	X																															
Repair / Delay Costs -- Not Able to Open/Close bridge		x	x																															
Inspection costs -- no damage		x	x																															
Other Track Defect / Wide Gage																																		
Repair or Replacement of Collapsed Bridge				X	x	x	x	x					x	x																				
Repair Costs -- Damage to Substructure/Superstructure				X	x	x	x	x					x	x																				
Train Derails due to Track Defect				x	x	x	x	x					x	x																				
Repair Track													X																					

X	=	probable match
O	=	possible match

Figure A2. Risk Control Matrix Page 2

	Protection							Scheduled Inspections								Existing Detection Systems										Advanced / Prospective Mitiagation Techniques											
Description of Loss	Highway Signs, Lights, etc	Bridge Lighting	Bridge Shielding (fender sys, etc)	Inner Guard Rail	Truss Guard Rails	Collision Posts (trusses)		Annual and Special Inspection	Track Inspector	Moveable bridge Inspection	Moveable Brdg Tender / Remote Brdg Operator	NDT	Underwater Inspection	Automated Track Inspe Vehicle		Inspection by others	High Water Detector	Weather Notification Network	High/Wide Load or Shifted Load Detector	Dragging Equipment Detector	Overload/Imbalanced Load Detector	Signal System	Rail Strain Measurement	Track Displacement Detector		Bridge Strike Detector	Mid Span Displacement	Self Diagnostic Moveable Bridges	Unattended Scour Monitoring	Remote Underwater Inspection	Bridge Presence Indication	Strain measurement	Tilt monitors	Fire Detection System	Fireproofing	Vehicle Borne Monitoring	Pile Displacement Detector
Track Buckle/Kink																																					
Repair or Replacement of Collapsed Bridge				X	x	x										X							x	x													
Repair Costs -- Damage to Substructure/Superstructure				X	x	x										X							x	x													
Train Derails due to Track Defect				x	x	x										X							x	x													
Repair Track																							x														
Foundation Problems																																					
Train Accident Due to Undetected Collapse								x	x					o		x						O		o			x				x		X				X
Repair or Replacement of Collapsed Bridge								x																			x						X				X
Train Derails due to Undetected Damage or Misalignment				x	x	x		x	x					o		x								x			x						X				X
Repair costs -- Bridge Misalignment/Movement								x																			x						x				X
Repair Costs -- Damage to Substructure/Superstructure								x																			x						x				X
Total "Probable"	6	13	13	21	20	20	0	17	24	8	10	4	5	8	0	28	4	4	7	2	10	3	4	10	0	6	14	8	5	5	8	4	9	4	4	4	10
Total "Possible"	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	7	0	8	0	0	0	1	0	0	0	0	9	0	0	5	0

X	=	probable match
O	=	possible match

Figure A3. Risk Control Matrix Page 3

Appendix B.
Preventable Annual Risk Exposure for Selected Systems

Service interruptions included in the potential preventable risk exposure per are shown in Tables B1-B12. Note that the total potential preventable risk exposure per year value is not corrected for missing data.

Table B1. Track Displacement Detector

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1982	Other Hydraulic-Bridge	15	0	$699,838
1993	Strike-Marine Traffic	103	47	$14,540,6504
1997	Other Hydraulic-Bridge	183	0	$8,069,557
1999	Track Buckle/Kink	0	0	$297,568
2000	Track Buckle/Kink	0	0	$25,867
2000	Other Hydraulic-Bridge	0	0	$112,509
2001	Track Buckle/Kink	0	0	$109,936
2002	Bridge Misalignment	0	0	$49,739
2003	Track Buckle/Kink	0	0	$13,452
2003	Track Buckle/Kink	0	0	$8,358
2003	Track Buckle/Kink	0	0	$44,179
2003	Hydraulic-Approach	0	0	$11,181
2005	Track Buckle/Kink	0	0	$9,689
2005	Other Hydraulic-Bridge	0	0	$20,131
2006	Track Buckle/Kink	0	0	$5,306
2007	Hydraulic-Approach	0	0	$ 5,800
2007	Other Hydraulic-Bridge	2	0	$729,456
2007	Bridge Misalignment	0	0	$18,873
2007	Strike-Hwy Traffic	0	0	$1,709
2008	Track Buckle/Kink	0	0	$47,974
			Total	$24,821,775

Table B2. Bridge Strike Detector

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1993	Strike-Marine Traffic	103	47	$14,540,650
			Total	$14,540,650

Table B3. High Water Detector

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1982	Other Hydraulic-Bridge	15	0	$694,656
1997	Other Hydraulic-Bridge	183	0	$7,962,202
2000	Other Hydraulic-Bridge	0	0	$14,351
2002	Other Hydraulic-Bridge	0	0	$3,857
2002	Other Hydraulic-Bridge	1	0	$113,058
2003	Scour	0	0	$3,218
2005	Other Hydraulic-Bridge	0	0	$15,623
2007	Scour	0	0	$17,110
2007	Other Hydraulic-Bridge	2	0	$560,494
2008	Other Hydraulic-Bridge	0	0	$85,715
2008	Scour	0	0	$105,938
2008	Other Hydraulic-Bridge	0	0	$11,349
			Total	$9,587,576

Table B4. Unattended Scour Monitoring

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1982	Other Hydraulic-Bridge	15	0	$699,837
1997	Other Hydraulic-Bridge	183	0	$8,069,557
2000	Other Hydraulic-Bridge	0	0	$112,509
2002	Other Hydraulic-Bridge	0	0	$59,431
2002	Other Hydraulic-Bridge	1	0	$139,733
2003	Scour	0	0	$110,491
2005	Other Hydraulic-Bridge	0	0	$20,131
2007	Scour	0	0	$17,110
2007	Other Hydraulic-Bridge	2	0	$729,456
2008	Scour	0	0	$223,098
2008	Other Hydraulic-Bridge	0	0	$605,436
2008	Other Hydraulic-Bridge	0	0	$51,332
2008	Other Hydraulic-Bridge	0	0	$51,332
			Total	$10,889,453

Table B5. Tilt Monitors

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1982	Other Hydraulic-Bridge	15	0	$694,656
1997	Other Hydraulic-Bridge	183	0	$7,962,202
1999	Foundation Problems	0	0	$16,891
2000	Other Hydraulic-Bridge	0	0	$14,351
2001	Failed Structural Member	0	0	$795
2001	Foundation Problems	0	0	$1,120
2001	Foundation Problems	0	0	$14,466
2002	Other Hydraulic-Bridge	0	0	$3,857
2002	Other Hydraulic-Bridge	1	0	$113,058
2003	Scour	0	0	$3,218
2003	Foundation Problems	0	0	$42,288
2004	Failed Structural Member	0	0	$84,949
2005	Other Hydraulic-Bridge	0	0	$15,623
2005	Foundation Problems	0	0	$5,049
2006	Foundation Problems	0	0	$17,116
2006	Foundation Problems	0	0	$8,863
2007	Scour	0	0	$17,110
2007	Other Hydraulic-Bridge	2	0	$560,494
2007	Failed Structural Member	0	0	$11,445
2007	Foundation Problems	0	0	$5,739
2008	Scour	0	0	$105,938
2008	Other Hydraulic-Bridge	0	0	$85,715
2009	Failed Structural Member	0	0	$12,655
			Total	$9,797,596

Table B6. Foundation Displacement Monitoring

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1982	Other Hydraulic-Bridge	15	0	$694,656
1997	Other Hydraulic-Bridge	183	0	$7,962,202
2000	Other Hydraulic-Bridge	0	0	$14,351
2001	Foundation Problems	0	0	$1,120
2002	Other Hydraulic-Bridge	0	0	$3,857
2002	Other Hydraulic-Bridge	1	0	$113,058
2002	Foundation Problems	0	0	$27,787
2003	Scour	0	0	$3,218
2005	Foundation Problems	0	0	$5,049
2005	Foundation Problems	0	0	$162
2005	Other Hydraulic-Bridge	0	0	$15,623
2006	Foundation Problems	0	0	$17,116
2006	Foundation Problems	0	0	$8,863
2007	Scour	0	0	$17,110
2007	Other Hydraulic-Bridge	2	0	$560,494
2007	Foundation Problems	0	0	$5,739
2008	Other Hydraulic-Bridge	0	0	$85,715
2008	Scour	0	0	$105,939
			Total	$9,642,058

Table B7. High Wide Shifted Load

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1999	Load Shift	0	0	$5,530
1999	Load Shift	0	0	$172,710
1999	Damage by Derailed Train	0	0	$85,121
2000	Load Shift	0	0	$69,284
2000	Load Shift	0	0	$2,878
2000	Damage by Derailed Train	0	0	$14,866
2000	Load Shift	0	0	$55,220
2001	Load Shift	0	0	$95,313
2001	Damage by Derailed Train			$27,273
2001	High/Wide Rail Carload	0	0	$7,053
2002	High/Wide Rail Carload	0	0	$2,223
2002	Load Shift	0	0	$185,376
2002	Damage by Derailed Train	0	0	$217,937
2002	Damage by Derailed Train			$27,273
2003	Damage by Derailed Train	0	0	$163,450
2003	Load Shift	0	0	$2,000
2003	Load Shift	0	0	$234,448
2003	High/Wide Rail Carload	0	0	$1,537
2003	Damage by Derailed Train	0	0	$20,935
2003	Damage by Derailed Train	0	0	$114,615
2003	Load Shift	0	0	$8,510
2004	Damage by Derailed Train			$136,364
2004	Damage by Derailed Train	0	0	$5,739
2004	Damage by Derailed Train	0	0	$121,292
2005	Damage by Derailed Train	0	0	$500,145
2005	Damage by Derailed Train	0	0	$215,494
2005	Damage by Derailed Train			$27,273
2005	Damage by Derailed Train			$27,273
2005	High/Wide Rail Carload	0	0	$6,312
2005	Load Shift	0	0	$26,148
2006	Damage by Derailed Train	0	0	$84,195

Table B7. High Wide Shifted Load (continued)

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
2006	Damage by Derailed Train	0	0	$12,723
2006	Load Shift	0	0	$7,035
2007	Damage by Derailed Train			$136,364
2007	Damage by Derailed Train			$27,273
2007	Damage by Derailed Train			$27,273
2007	Damage by Derailed Train			$27,273
2007	Load Shift	0	0	$3,687
2007	Load Shift	0	0	$23,952
2007	Damage by Derailed Train			$27,273
2007	Load Shift	0	0	$33,554
2007	Load Shift	0	0	$17,804
2007	Load Shift	0	0	$41,176
2008	Damage by Derailed Train			$136,364
2008	Damage by Derailed Train			$27,273
2008	Damage by Derailed Train	0	0	$129,107
2008	Damage by Derailed Train			$27,273
2008	Strike-RR Traffic			$27,273
2009	Damage by Derailed Train			$136,364
2009	Damage by Derailed Train			$27,273
2009	Damage by Derailed Train			$27,273
2009	Damage by Derailed Train			$27,273
2009	Damage by Derailed Train			$27,273
			Total	$3,641,910

Table B8. Rail Strain Measurement

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1999	Track Buckle/Kink	0	0	$276,203
1999	Broken Rail on Bridge	0	0	$55,548
2000	Track Buckle/Kink	0	0	$17,808
2001	Track Buckle/Kink	0	0	$38,880
2003	Track Buckle/Kink	0	0	$10,745
2003	Track Buckle/Kink	0	0	$4,822
2003	Track Buckle/Kink	0	0	$37,313
2005	Track Buckle/Kink	0	0	$590
2005	Broken Rail on Bridge	0	0	$15,155
2005	Broken Rail on Bridge	0	0	$39,393
2005	Broken Rail on Bridge	0	0	$29,615
2005	Broken Rail on Bridge	0	0	$28,672
2006	Track Buckle/Kink	0	0	$685
2006	Broken Rail on Bridge	0	0	$97,631
2007	Broken Rail on Bridge	0	0	$32,699
2009	Broken Rail on Bridge	0	0	$140,687
			Total	$826,446

Table B9. Mid Span Displacement Detector

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
1999	Failed Structural Member	0	0	$9,859
2001	Foundation Problems	0	0	$1,120
2001	Failed Structural Member	0	0	$795
2001	Foundation Problems	0	0	$14,466
2002	Foundation Problems	0	0	$27,787
2003	Scour	0	0	$3,218
2003	Foundation Problems	0	0	$42,288
2004	Failed Structural Member	0	0	$84,949
2005	Foundation Problems	0	0	$5,049
2005	Failed Structural Member	0	0	$39,393
2006	Foundation Problems	0	0	$17,116
2006	Foundation Problems	0	0	$8,863
2007	Foundation Problems	0	0	$ 5,739
2007	Failed Structural Member	0	0	$11,445
2009	Failed Structural Member	0	0	$12,655
			Total	$284,741

Table B10. Strain Monitoring

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
2004	Failed Structural Member	0	0	$84,949
			Total	$84,949

Table B11. Fire Detector

Year	Primary Hazard	Number of Injuries	Number of Fatalities	Potential Preventable Risk Exposure per Year
2009	Fire	0	0	$635,508
2009	Fire	0	0	$56,143
2010	Fire	1	1	$1,131,245
			Total	$1,822,896

Table B12. Vehicle Borne Monitoring

Year	Primary Hazard	Number of Injuries	Number Fatalities	Potential Preventable Risk Exposure per Year
1999	Foundation Problems	0	0	$16,891
1999	Failed Structural Member	0	0	$9,859
2001	Failed Structural Member	0	0	$ 795
2001	Foundation Problems	0	0	$1,120
2001	Foundation Problems	0	0	$14,466
2003	Foundation Problems	0	0	$42,288
2004	Failed Structural Member	0	0	$84,949
2005	Foundation Problems	0	0	$5,049
2005	Failed Structural Member	0	0	$39,393
2006	Foundation Problems	0	0	$17,116
2006	Foundation Problems	0	0	$8,863
2007	Failed Structural Member	0	0	$11,445
2007	Foundation Problems	0	0	$5,739
2009	Failed Structural Member	0	0	$12,655
			Total	$270,626

Abbreviations and Acronyms

AAR	Association of American Railroads
AREMA	American Railway Engineering and Maintenance and Way Association
BNSF	Burlington Northern Sante Fe
CBA	cost-benefit analysis
CP	Canadian Pacific
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
GIS	geographic information system
LTBP	Long-Term Bridge Performance
MNDOT	Minnesota Department of Transportation
NDE	nondestructive evaluation
NS	Norfolk Southern
RBSID	Railroad Bridge Service Interruption Database
TADS®	Trackside Acoustic Detection System
TAG	technical advisory group
TRB	Transportation Research Board
TTCI	Transportation Technology Center, Inc.
UP	Union Pacific
Volpe	John A. Volpe National Transportation Systems Center