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CURRENT RESEARCH TOPICS: RAILROAD BRIDGES AND STRUCTURAL ENGINEERING



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The Newmark Structural Engineering Laboratory (NSEL) of the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign has a long history of excellence in research and education that has contributed greatly to the state-of-the-art in civil engineering. Completed in 1967 and extended in 1971, the structural testing area of the laboratory has a versatile strong-floor/wall and a three-story clear height that can be used to carry out a wide range of tests of building materials, models, and structural systems. The laboratory is named for Dr. Nathan M. Newmark, an internationally known educator and engineer, who was the Head of the Department of Civil Engineering at the University of Illinois [1956-73] and the Chair of the Digital Computing Laboratory [1947-57]. He developed simple, yet powerful and widely used, methods for analyzing complex structures and assemblages subjected to a variety of static, dynamic, blast, and earthquake loadings. Dr. Newmark received numerous honors and awards for his achievements, including the prestigious National Medal of Science awarded in 1968 by President Lyndon B. Johnson. He was also one of the founding members of the National Academy of Engineering.

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ABSTRACT

Railroad infrastructure must be maintained safely and reliably for both owners and users. Railroad bridge expenditures in particular represent about 10% of the annual capital investment for Class I railroads in the United States (U.S.). Due to the lack of flexibility of railroad networks, railroads cannot afford not to repair or replace bridges that should be either partially upgraded or completely renovated. If they fail to do so, maintenance expenses and/or structural failure could cause railroads to lose money that would have been saved if part of it had been properly budgeted and used in the first place. Beyond these financial concerns associated with railroad bridge management, railroads (which are private commercial enterprises in the U.S.) are widely recognized for placing a high priority on safety. Academia, government, and railroad bridge engineering agencies have, over the years, all formally studied a variety of railroad bridge research topics. In the past, workshops have assisted railroad institutions toward directing research efforts based on the current needs of the railroad bridge structural engineering community. This report is the result of a new survey-based study entitled “Current Research Topics: Railroad Bridges and Structural Engineering.” The lead author of this report planned and conducted the survey during the 2009-2010 academic years, and comprised the results and findings during 2011. Research topics were selected and prioritized following the results of a detailed telephone survey conducted with sixteen experts on railroad bridges and structural engineering in North America. This report includes a literature review that was developed to follow up on topics discussed during the course of the survey interviews. In addition, other focused conversations with key professionals in both the railroad bridges and structural engineering communities (including experts on associated technologies from academia and industry) have been incorporated into this report. The increased nationwide attention toward high-speed railroads has also been addressed. Finally, new federal regulations affecting railroad bridge management in the U.S. have been examined and included. This survey-based study identifies the management of railroad bridges as a primary concern for railroad bridge structural engineers today. Field assessment, especially as it relates to bridge capacity, is of particular interest. The near-term implementation of Structural Health Monitoring (SHM) into railroad bridge management has been identified as a potential tool for railroad bridge management. Finally, current and future research in this and other related areas is briefly discussed and proposed. In summary, this report identifies current structural engineering research topics of interest for railroad bridges in North America. In particular, the railroad bridge structural engineering community finds the assessment of bridge performance under traffic loading by using emerging SHM techniques to be a top research interest. As a consequence, SHM implementation for railroad bridges management should be given high priority for research and development.

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INTRODUCTION

1.1 Motivations for this study

The Federal Government has unveiled new efforts toward planning for the development and implementation of high speed passenger rail service in the United States (U.S.). In October 2009, President Obama proposed a \$5 billion investment towards High Speed Rail (HSR) as part of the 2010 budget (CNN, 2009). On January 27, 2010, the President announced more than \$8 billion dollars in funding from the Federal Railroad Administration (FRA) to begin the construction of high speed railroads (Freemark, 2010).

In parallel with this announcement by the U.S. Government, recent studies conducted by the IBM Corporation (Dierkx, 2009) listed an 88% forecast demand increase for domestic freight Railroads (RR) by 2035. In a different publication, data collected by the Transportation Research Board (TRB) and co-authored with the Association of American Railroads (AAR) estimated the cost of infrastructure expansion needed to match the 2007-2035 estimated growth at \$148 billion (in 2007 dollars) (Cambridge Systematics, Inc., 2007).

As a consequence, media attention to U.S. railroads has dramatically increased in recent years, capturing all sectors of American society in general, including public and private agencies like IBM, TRB, and AAR.

Railroad bridges are unique structures, in part due to the very nature of the railroad industry – North American railroads are privately owned, while the large majority of railroads in other countries are publically funded. It is partially because of this that the overall motivation and purpose for railroad bridge research (modeling, testing, validation, and verification) should be to maintain bridges within safe conditions and to assure satisfactory operational performance (Byers and Otter, 2006). Safety and economics are constantly referred to and quoted in this report as the basis of railroad bridge engineering. Another factor of interest for railroad bridges lies in the fact that, whereas highway bridges can be replaced or repaired in most cases by diverting their traffic to a different route, this is typically not possible with railroads. Moreover, railroad traffic cannot be stopped, because interrupted traffic means money lost to the railroad industry. As a consequence, bridge replacements or repairs, whenever they are necessary, must be carried out under traffic (and/or working around very small windows of down-time). This makes the operation, design, construction, and maintenance of railroad bridges more challenging than for highway bridges and other conventional transportation structures.

Some sources and surveys count about 77,000 railroad bridges in the U.S. owned by freight companies (Richards, 2007a; GAO, 2007; FRA, 2008a; FRA, 2008b), and about 1,300 owned by Amtrak (Cowan, 2004). However, the FRA estimates the total number as being closer to 100,000 railroad bridges (ENSCO, 1994; FRA, 2008a, 2008b, 2010b), when including commuter, medium, and short railroad companies not typically reached by general inventories in the U.S. The total replacement cost of this railroad bridge inventory is estimated at about \$100 billion (Vantuono, 2008).

It is of general interest than even when the exact current conditions of these bridges are not made public, the FRA generally accepts that railroad bridges are safe (Richards, 2007a). This general trust in railroad bridges partially relies on the fact that, according to the U.S. Government Accountability Office (GAO), there has not been a fatality associated with a rail bridge failure since 1957 (Miller, 2007). However, it is worth noticing that this same agency also points out that, even with more than 40% of the nation's freight tonnage being carried by railroads, the FRA does fairly little monitoring of the condition of railroad bridges (Miller, 2007). Other sources stress that it is the extensive maintenance work annually performed by railroads which keeps bridges safe and reliable until they eventually need to be replaced. These same sources clarified that the main reasons for their replacements are often a combination of structural and functional (Richards, 2007b).

Up until very recently, the Federal Government has allowed railroads to manage their bridges on their own. In other words, railroads have been responsible of conducting their own inspection, maintenance, rating, and safety programs. However, in the last few years, this situation has changed. In the first place, attention towards safety of railroad bridges notably increased after the collapse of a small railroad timber trestle that was carrying elements of the space shuttle in 2007 (Richards, 2007a). This added to the overall concern of the general public about bridges, both highway and railroad after the collapse of the I-35W Mississippi River highway bridge on August 1, 2007 (Reid, 2007). More recently, on September 13, 2010, the FRA implemented new regulations regarding railroad bridge management (FRA, 2010b).

Consequently, a new management scenario is unfolding for present and future years in North American railroad bridges. Chapter 4 includes references related to recommended literature and regulations, as well as the consequences of these new regulations to the railroad and a list of research topics related to these new regulations.

The following section provides a general description to the philosophy of North American railroads infrastructure maintenance and management.

1.2 Introduction to railroad infrastructure philosophy

Among the most important elements of railroads, having reliable infrastructure is a key to guaranteeing a robust network for owners, clients, and society in general. During the last few decades, the loads, speeds, and capacities of railroads have rapidly increased from their original values. Bridges carrying these trains have had to be inspected and re-rated in order to ensure they can safely operate under the new conditions. According to the International Heavy Haul Association (IHHA), the weight of the equipment has been increased up to 70% since 1970 (Unsworth, 2009). To maintain a reliable infrastructure for both owners and clients in the future, a number of railroad bridges will need to be either repaired or replaced (and almost all of them will require ongoing inspection and assessment).

The availability of the system for railroad traffic is a paramount demand from the railroad owner when the design and construction of a new bridge (or the replacement of an existing one) is considered. Figure 1.1 shows a recent partial replacement of a railroad bridge where older timber trestle elements were substituted by a new 80-ft (24-m) steel Deck Plate Girder (DPG). This bridge replacement was done in less than twelve hours;

the last train crossed over the timber trestle at 6:40 A.M. and the first train crossed the new DPG at 6:30 P.M. on that same day.

People who are not directly involved in the transportation industry often overlook how critical railroad transportation is to the economic well-being of the U.S. However, it is generally accepted by railroad industry experts that a large percentage of traffic is interchanged between two or more railroads between its origin and destination. In terms of tons-per-miles, more than 25% of the freight is transported by railroads in the U.S., according to the Research and Innovative Technology Administration (RITA) of the Bureau of Transportation Statistics of the U.S. Department of Transportation (USDOT) (2000).



Figure 1.1. Railroad timber trestle bridge replacement, using a DPG member.

The Surface Transportation Board (STB) divides U.S. railroads in three categories based on operating revenues. Class I railroads have annual revenues exceeding \$319.2 million (Armstrong, 2008). According to the AAR Class I railroads represent 67% of the U.S. total railroad freight mileage (FRA, 2010a). This same source remarks that 90% of railroad employees work for Class I railroads (see further information about Class I railroads in section 1.4). Based on these two percentages, Class I railroads are critical to the entire U.S. railroad freight transportation system.

Analogous to the importance of railroad transportation to the economy of the nation is the importance of railway bridges and structures in the overall railroad network. Bridges must be designed in a manner that will allow current and future safe and efficient movement of rail traffic. Of significant importance to the railroad industry is keeping the railroad network fluid and free of service disruptions, which can wreak havoc on railroad network operations as well as on the operations of the railroad's customers (New York

Times, 2006). Therefore, railroad companies look very closely at the integrity of their railroad bridges.

Structural bridge engineers work for the railroads to design, build, maintain, assess, and replace bridges. These engineers are responsible for the reliability of the railroad network with respect to the bridges that comprise it. According to the IHHA, “the extension of asset life through research and rational assessment is critical to the continued safety and economics of Heavy Haul (HH) operations” (IHHA, 2009). Almost 100 years earlier, acclaimed railroad bridge consulting engineer Waddell (see Figure 1.2) stressed in his book, *Economics of Bridgework*, the importance of both safety and economics for bridge maintenance (Waddell, 1921).

It can be concluded that the efficient usage and management of bridges guarantees safe and profitable operations for the railroads and their customers. The next section in this report briefly explains financial aspects related to railroad bridges and structures in North America: Railroad bridge economics related to bridge (a) design, (b) maintenance, and (c) replacement.

1.3 Railroad bridge design, maintenance, and replacement economics

The main role of railroad bridge structural engineers is to avoid any flaws in design, performance, or maintenance that could potentially cause loss of life and/or loss of capital investments in maintenance and replacement. In other words, as explained in the previous section, bridge structural engineers must ensure the reliability of the railroad network by assessing and maintaining the reliability of their bridges.

How much do bridges cost the railroads?

The capital invested toward railroad bridges and structures by the railroads, relative to their operating expenses, can be a parameter used to illustrate the importance of bridges to this industry in relationship to their entire capital investments. According to the AAR (2002, 2006, and 2009), the expense (costs) directed towards structures and maintenance of way (i.e., bridges, tunnels, and clearance of track) represent about 17% of their total expenses. On the other hand, the cost of bridges to a Class I railroad’s basic capital investment is shown in Figure 1.3, where the cost of bridges represents almost 10% of the total annual basic capital investment from its total budget (Ferryman, 2008). This percentage remains relatively unchanged from similar data presented three years earlier (Ferryman, 2005). Bridge expenditures represent a significant percentage of railroad’s total budgets, which underlines the importance of railroad bridge management for railroad companies.

Structural engineers make decisions about the upgrading, maintenance, and/or replacement of infrastructure (and specifically bridges) in part based on an economic approach to the effects of their intervention (i.e., replacement versus retrofit) (Russo et al., 2003). This economic approach is not uncommon in the broader bridge engineering community. For example, J.A.L. Waddell wrote books and articles defending the importance of economics in all lines on engineering work (Waddell, 1924) and about applying economics to bridge engineering (Waddell, 1921). However, the importance of

economics in engineering today related specifically to railroad bridges is not completely understood or studied well enough.



Figure 1.2. J.A.L. Waddell (Waddell, 1924).

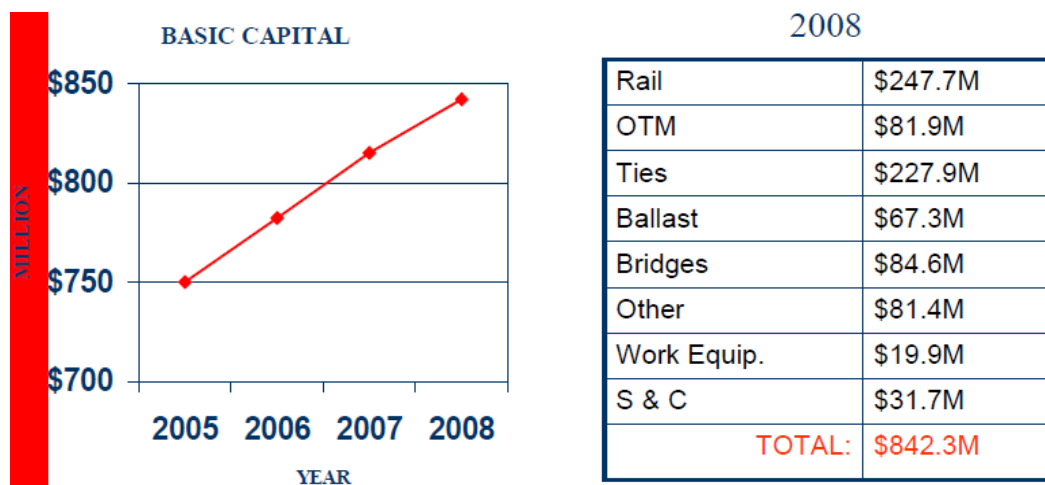


Figure 1.3. 2008 CN basic capital investing (Ferryman, 2008).

The railroad engineering community places a greater emphasis on the economics related to their structures in comparison to other transportation entities. Because railroads are private companies searching for possible reductions of in-house costs to increase income benefits, U.S. railroads have promoted and developed studies directed at the cost-effectiveness of retrofitting railroad bridges (Day and Barkan, 2003; Resor et al., 2001). These studies have shown the main goals of railroad companies toward maximizing the use of their budget and investment for railroad bridge design, construction, assessment, maintenance, and replacement. This is really no surprised when considered in light of a historical observation of the legendary Hay (see Figure 1.4), who stated that one of the main purposes of railroads is “to secure profit” (Hay, 1982).

Figure 1.5 shows the productivity of the railroad industry as compared with other types of transportation. This illustration, from the USDOT, describes the increase in productivity of railroads over the last twenty years in comparison to other means of transportation in the U.S. Productivity is defined as the output per employee. Of special interest is the significant difference between the line-haul railroads in comparison to the general long-distance freight trucking industry. During this period of time, the relative productivity of railroads has doubled, surpassing direct competitors’ own indexes. Finally, this plot helps one to better understand the economics of railroad infrastructure, and its relative benefits from a global transportation perspective versus air transportation and postal service productivities (USDOT, 2009).

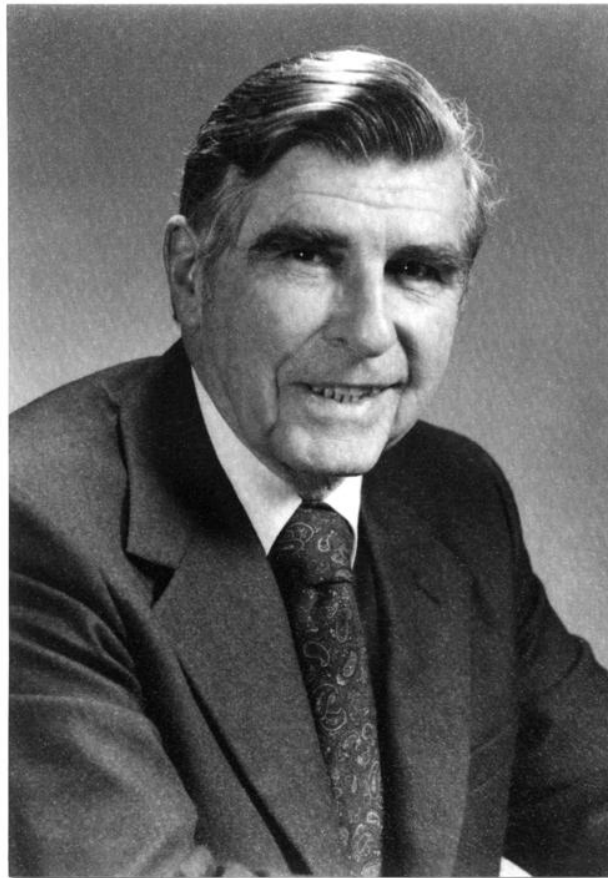


Figure 1.4. Prof. W. W. Hay (RailTEC, 2011).

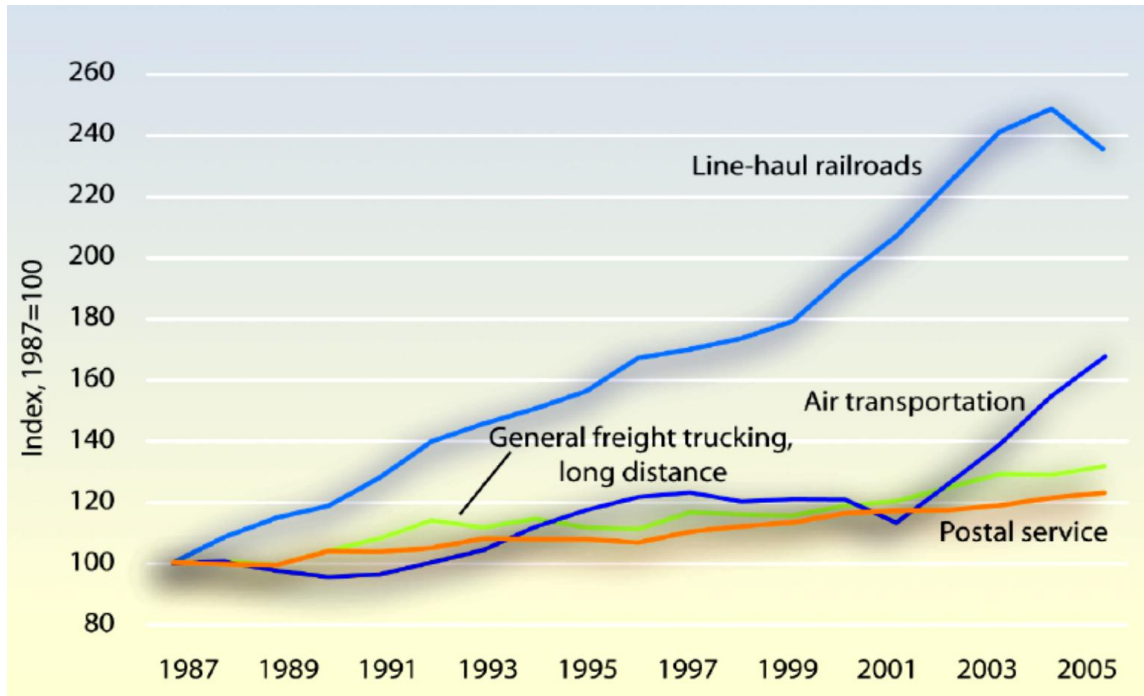


Figure 1.5. Productivity in selected transportation industries: 1987-2005 (output per employee,¹ Index, 1987=100) (USDOT, 2009).

1.4 Railroad companies in the United States

Today there are seven major (“Class I”) railroads in North America as categorized by operating revenues. Norfolk Southern Corporation (NS) and CSX Corporation (CSX) primarily serve the eastern U.S., and the western U.S. is served by Burlington Northern Santa Fe (BNSF) and Union Pacific (UP), while Kansas City Southern (KCS) operates in the south-central U.S. Finally, Canadian National (CN) and Canadian Pacific (CP) operate not only in Canada, but also throughout portions of the northern and central U.S., with CN operating south to the Gulf of Mexico. In addition to the Class I railroads, there are over 500 regional and short line railroads throughout North America.

1.5 Railroad institutions mentioned in this report

Figure 1.6 (AAR, 2012) shows the U.S. freight railroad network, including the seven Class I railroads and the medium and short lines, a legacy of the first transcontinental railroad in the world, described by historian Stephen E. Ambrose in his book *Nothing Like It in the World: The Men Who Built the Transcontinental Railroad 1863-1869* (2000).

¹ Based on the number of paid hours. Real gross domestic product is the business and nonfarm business sectors in the basis of the output components of the productivity measures. These output components are based on and are consistent with the National Income and Product Accounts (NIPA), including the gross domestic product (GDP) measure, prepared by the Bureau of Economic Analysis (BEA) of the U.S. Department of Commerce.

This report mentions several railroad institutions that cannot be all covered on an individual basis. However, a selection of the most significant ones is provided based on both their relevance to the research topics being discussed and their number of appearances throughout the elaboration of the study. The four railroad institutions presented in this study are:

- (a) Association of American Railroads (AAR)
- (b) Federal Railroad Administration (FRA)
- (c) American Railway Engineering and Maintenance of Way Association (AREMA)
- (d) Transportation Technology Center, Inc. (TTCI)

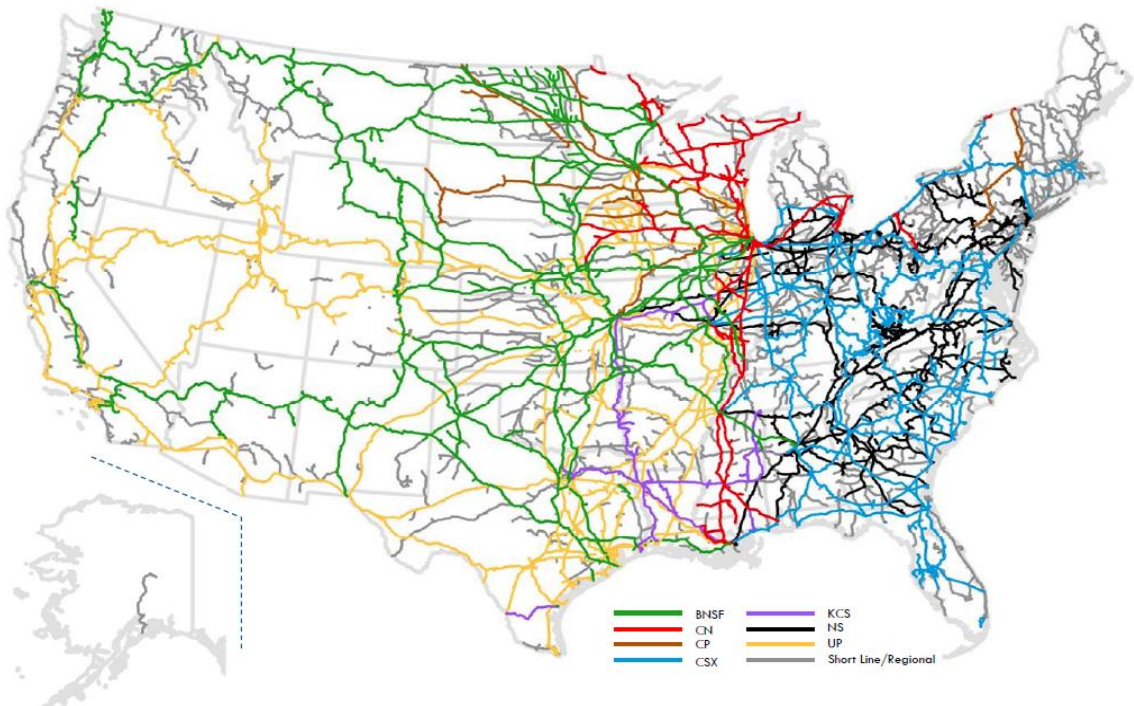


Figure 1.6. The U.S. freight railroad network² (AAR, 2012).

1.5.1 Association of American Railroads (AAR)

The AAR is an industry group that includes the most representative freight railroad companies in North America, including Canada, Mexico and the U.S. Amtrak and other regional railroads are also members. Suppliers to the railroad industry are also associates of the AAR. The AAR produces policies and technology to ensure safe and efficient railways, and its size and scope places it as a worldwide leader in railroad policies. It is recognized as the standard setting organization for railroads in North America (AAR, 2011).

According to its main website (AAR, 2011), there are three subsidiaries that produce research of interest to the railroad industry: (a) the Transportation Technology Center Inc.

² Map shows rail line ownership based on 2011 National Transportation Atlas Database published by the USDOT's Bureau of Transportation Statistics (BTS).

(TTCI) (section 1.5.4); (b) Railinc Corporation, in charge of developing information technology and shipment management, and (c) Railroad Research Foundation (RRF), focused on the government research concerns about various rail freight and infrastructure merging areas.

More information about AAR and subsidiaries goals and research activities can be found at <http://www.aar.org/>.

1.5.2 Federal Railroad Administration (FRA)

The FRA, created in 1967, operates under the USDOT. According to their main website, “the purpose of FRA is to: promulgate and enforce rail safety regulations; administer railroad assistance programs; conduct research and development in support of improved railroad safety and national rail transportation policy; provide for the rehabilitation of Northeast Corridor rail passenger service; and consolidate government support of rail transportation activities” (FRA, 2010a).

As a provision for the Railroad Bridge Safety Policy, the FRA requires railroad bridge departments to follow the *Manual for Railway Engineering* (MRE) by AREMA (USDOT, 2007).

More information about FRA can be found at <http://www.fra.dot.gov/>.

1.5.3 American Railway Engineering and Maintenance of Way Association (AREMA)

Owing to the private nature of North American Railroads, each railroad has internal standards and/or codes that regulate the design, construction, inspection, and maintenance of their bridges and structures. In addition to these private regulations that each railroad may mandate for their railroads design and construction, AREMA provides “recommended practices” as commonly accepted guidelines in their AREMA Manual, also known as the *MRE* (AREMA, 2009). Divided into forty-one committees or teams, AREMA functions as a widely accepted arbiter for both the technical and practical aspects affecting railroad operations.

As done in the overall railroad community, railroad bridge structural engineers frequently use AREMA as a reference point when discussing the state-of-the-art and state-of-practice for railroad bridges. Throughout this report, many MRE chapters and AREMA members will be referenced. A description of the committees pertaining to structural engineering is listed in Table 2.5 and Table 2.7. A more detailed description of each committee can be obtained from the AREMA references (AREMA, 2009).

Committee 10 (Construction and Maintenance of Structures) is of particular interest to the research topics discussed in this report. The main committees related to bridges and structural engineering cover the following areas: concrete, steel, timber, and seismic design (see Table 2.5).

More information about the AREMA can be found at <http://www.arema.org/>.

1.5.4 Transportation Technology Center, Inc. (TTCI)

The TTCI is a wholly owned subsidiary of the AAR, who assumed responsibility for it in 1982. Under the control contract of the FRA, the Transportation Technology Center

(TTC) is owned by the USDOT (AAR, 2011). The TTCI carries out research and testing related to all different aspects of railroads in North America and other regions. TTCI headquarters are located near Pueblo, Colorado. The facility was initially dedicated in 1971 as the High Speed Ground Test Center (HSGTC), but in 1974 the government changed the name to TTC and focused its emphasis toward enhancing the safety and efficiency of conventional railroading. In 1995, the Pueblo site's name was changed to Transportation Technology Center, and in 1998 it became TTCI (to facilitate contract research from entities other than AAR members).

The TTC has 48 miles of track, subjected to real train loading that can test all the different aspects of track system performance, design, and maintenance, including various railroad bridges being tested under different loading conditions. Among other services for railroad bridges testing, TTC has the Facility for Accelerated Service Testing (FAST) (AAR, 2011).

Initially, no bridge research was conducted at the TTC, and was instead handled by the Chicago center, through an AAR office in downtown Chicago, Illinois. In 1995, the personnel and equipment from this office (and from the Washington System Center) were relocated to TTC.

In November 1997, the steel bridge at FAST was placed to initially test bridge ties, decks, fastening systems, rail and anchoring patterns, and bridge approaches. It soon expanded into a bridge fatigue and repair test, as well as a test-bed for evaluation of bridge Non-Destructive Evaluation (NDE) technologies.

In December 2003, two prestressed concrete bridges were placed in service at FAST. The main purpose was to: evaluate performance of various concrete spans under Heavy Axle Load (HAL) traffic, evaluate effects of tie type and ballast depth on bridge impact and track maintenance, and evaluate performance of bridge deck waterproofing materials. It has since been used to evaluate performance of ballast mats, as well as composite beam spans.

On March 29, 2011, FRA Administrator Joseph Szabo and TTCI Board of Directors Chairman Edward Hamberger signed the FRA Care, Custody and Control Contract with TTCI for an additional 10-year period, concluding in September 30, 2022. This Contract was signed "to maintain and improve the facilities at the TTCI in Pueblo, Colorado and to enhance the use of those facilities for transportation research, development, security, training, and test activities" (AAR, 2011).

More information about the TTCI can be found at <http://www.aar.com/>.

1.6 Last 70 years of research on railroad bridges in the U.S.

Historically, the AAR has developed numerous studies in collaboration with U.S. universities involving railroad bridges and structural engineering (Byers and Otter, 2006). Several studies were reported between 1938 and the late 1960s as results of research conducted by the AAR.

However, between 1970 and 1990 very little railroad bridge structural engineering research was documented. In 1987, the National Science Foundation (NSF) sponsored a workshop about railroad bridge research needs at the University of Illinois at Urbana-Champaign (UIUC). The two main priorities coming out of this workshop were related to

the field measurement of static and dynamic stresses and the investigation of the Impact Factor (IF) and its effects.

After this workshop, the NSF funded both AAR and UIUC research as part of a railroad bridge research initiative. Between 1990 and 2005, that funding helped to generate eighty-one bridge-related investigations, thirty reports, and numerous articles prepared by the AAR and the TTCI.

Byers and Otter (2006) reported that the main topics of these studies fell within the following areas:

1. Current level of knowledge
2. Changes in technology
3. Field performance of bridges
4. Changes in design and construction costs
5. Changes in maintenance costs and service life
6. Changes in loadings

Summaries of the studies collected by Byers and Otter (2006) regarding the railroad research carried out during those years are listed in Table 1.1, Table 1.2, and Table 1.3.

Table 1.1 shows the 1987 Top Research Needs of Railroad Representatives. The two columns referring to rankings show the assigned priorities from the RRs and from the entire group of participants in the workshop. The number of reports refers to the subsequent number of reports that have been generated in the ensuing 18 years since the workshop of 1987.

Table 1.1. Description of research need (Byers and Otter, 2006).

Research need	Ranking RR	Ranking all	Number of reports
Field measurements of static and dynamic stresses	1	1	14
Investigate IF and its effects	2	3	
Determine LFs transmitted to bridges	5	4	9
Effects of variable load histories on fatigue life	3	2	7
Develop ways to prolong the life of old bridges	9	11	
Develop methods for determining remaining life	6	10	
Develop realistic IF criteria and load factors for RC	8	9	
Rating procedures based on field tests and analysis	7	8	
Develop reliable NDT techniques for timber	10	6	
Develop better analysis procedures for design	4	5	

Table 1.2 lists the broad ranging railroad bridge research topics addressed in these studies as of 2006. These titles reflect the main areas that benefitted from the research

generated during the 18 years following the NSF Workshop, with the research areas grouped into five main categories.

Table 1.2. AAR and UIUC research topics between 1987 and 2005 (Byers and Otter, 2006).

Knowledge acquired by the AAR and UIUC research
Bridge behavior and bridge loading
Evaluation of the effects of changes in loading of bridges
Extension of the service lives of bridges
Reduction of the cost of required maintenance and upgrading of existing bridges
Investigation of ways to reduce the demand on bridges

Table 1.3 identifies future challenges in research, based in part on the outcomes from previously conducted research involving railroad bridges. (The studies carried out during those 18 years typically identified future research demands in their conclusions). This table lists future research needs across six different areas.

Table 1.3. Future challenges for railroad bridges identified in recent AAR research (Byers and Otter, 2006).

Challenges remaining for future research topics
Increased traffic density and train speeds
New rolling stock and locomotive equipment
Increasing amounts of heavy-axle-load traffic
Increasing constraints on construction and replacement times
Better performance monitoring tools
Better materials

Many results of the AAR’s research carried out in these 18 years were included in the AREMA recommended practices for design and construction. Modified chapters involved steel, concrete, foundations, and seismic design (Byers and Otter, 2006). The sections modified as a result of the research carried out during those years include those relating to:

- Guidelines for Design and Rating of Bridges
- Fatigue
- Impact Factor (IF)
- Longitudinal Force (LF)
- Post-earthquake Operations Guidelines

In conclusion, the 1987 NSF Workshop proved to be a very valuable tool for railroads in determining and prioritizing research topics for railroad bridges in North America. The

positive effect of this workshop is well reflected in the number of research reports and studies published in subsequent years. This proves the importance of identifying research needs to better select and conduct research that will be valuable for the railroads.

1.7 Motivations for a survey-based study

In recent years, railroad bridges have been the object of only limited attention by authorities, the public, and research institutions. Thus the major areas of interest for structural engineering research related to railroad bridges today are not well known by the broader structural engineering community. Research dollars can best be directed toward areas that need improved knowledge development, once those have been defined and prioritized. A survey has been identified as a useful tool to determine these potential structural engineering research topics for railroad bridges.

The survey was conducted in the form of personal interviews with diverse and significant members of the structural engineering community around the U.S. railroad bridge industry. Although the primary emphasis of this survey was directed toward structural engineering topics, opinions and input from other important experts in the field of bridge engineering, such as bridge inspectors and bridge managers were also included. The content and format of the interviews are described in *Chapter 2*. Findings from this series of interviews can help determine which areas are of most interest to the structural engineering community involving the design, construction, inspection, assessment, and/or maintenance of railroad bridges.

1.8 Purpose and structure of this report

Similar to the workshop carried out at UIUC in 1987, this study's main goal is to identify potential research topics involving structural engineering and railroad bridges in the U.S. For this purpose, the researchers interviewed sixteen North American structural engineering experts on railroad bridges. The interviewees were presented with a listing of pre-selected topics related to structural engineering and railroad bridges. Then, individual interviews were conducted to collect their experience and opinions about these research topics. The content, elaboration, and description of the interviews are included in *Chapter 2*.

Chapters 3, 4, 5, and 6 list the different research topics identified from the survey. Findings and suggestions from additional literature reviews recommended during the evolution of the surveys have been incorporated into each of these chapters.

Chapters 3 and 4 involve design and management of railroad bridges. These two chapters included an in-depth description for each topic. *Chapters 5 and 6* cover those research areas related to (1) construction and maintenance and (2) any "other" area, respectively. These later chapters describe their research areas with less detail than the previous two chapters.

Chapter 3 lists topics related to the design of railroad bridges. The topics selected are not necessarily exclusive from other chapters, but they are considered to have a strong governing entity related to design. This chapter includes potential research topics related to HSR and railroad bridge structural engineering.

Chapter 4 presents areas of study that are related to railroad bridge management. This includes a special section that deals with existing aging timber trestles, given their continuing relevance for many railroads throughout North America.

Chapter 5 includes topics pertaining to the maintenance and construction of railroad bridges.

Chapter 6 lists other topics collected during the course of the survey. The research areas listed in this chapter do not strictly fall within any of the previous categories, and are therefore grouped under an independent section.

Chapter 7 collects the overall results obtained from all the interviews and present summaries of the different findings gathered during the interview process.

Finally, *Chapter 8* includes conclusions and recommendations for future research in railroad bridges in the context of structural engineering.

The section entitled REFERENCES lists related literature that is mentioned in this report and is included at the end of the main document.

There are four APPENDICES listing additional information about the survey interviews that the authors of this report consider to be of interest to readers.

APPENDIX A lists short biographies of the participants who were interviewed during the development of this report.

APPENDIX B notes a number of people additionally consulted on special aspects during the elaboration of this report.

APPENDIX C shows the current classification of railroad tracks related to traffic velocities today in the U.S. (FRA, 2009).

APPENDIX D compiles the different acronyms employed during this report.

Summary results from this research were published in the September 2011 issue of *Railway Track & Structures*, to help stimulate additional input from the broader railroad community in regard to future research prioritization (Moreu and LaFave, 2011).

SURVEY LAYOUT

2.1 Introduction: description of the 1987 National Science Foundation (NSF) Workshop

On October 28 and 29, 1987 the UIUC hosted a workshop entitled “The National Workshop on Railway Bridge Research Needs.” The objective of that workshop was to identify the most important research topics regarding railroad bridges and structural engineering. By determining these critical research topics, the workshop provided a potential course of action for research funds investment, so that funding for research could be efficiently directed to the industry needs when such funds became available.

A group of fifty-three railroad bridge structural engineers from all over North America (including Canada and Mexico) participated in the workshop. These participants included eighteen railroad engineers, thirteen consulting engineers, eight research engineers from the AAR, and fourteen university researchers. Both current and retired railroad engineering leaders were in the group.

The following literature review outlines research projects conducted as a consequence of the workshop (Groskopf, 1990; Anonymous, 1994b). Details about the organization of the workshop, the list of topics selected and discussed, and a summary of the findings can be found in a report published by the AAR (Foutch, 1989).

2.1.1 Connection between the 1987 NSF Workshop and motivations for this survey-based study

As shown in Chapter 1, the history of railroad research carried out in the 50 years prior to the 1987 NSF Workshop demonstrated the necessity for a meeting to best identify the future research needs for railroad bridge structural engineering. As a consequence of the publication of the findings of this meeting, research about railroad bridges increased between 1990 and 2005.

Twenty-five years have now passed since this meeting of professionals related to railroad bridges structural engineering took place. Today, the need for a new “meeting” to identify current research needs in North America is overdue. The reasons are as follows:

- 1) According to Byers and Otter (2006), and as noted in Chapter 1, a cycle of fertile research production versus a sterile research environment has alternated over the last 70 years. As proven in 1987, an identification of the research needs by recognized experts in the field may help to generate research topics that satisfy industry needs for a period of about 20 years. This 20 years cycle has passed, so a new workshop between railroad bridge experts is due. Hopefully, such a meeting will generate productive outcomes as before.
- 2) Since 1987, the year of the previous workshop, the railroad bridge structural engineering environment and community has substantially changed:

- a) Railroad bridge owners, contractors, and consultants have received a more specialized and in-depth academic education over the last few decades. These structural engineers are now in charge of the design, construction and management of railroad bridges. Today, only three decades later, it is not unusual to hold a PhD and work for a railroad bridge department, which was not the case in the 1980s.
- b) The societal environment has changed substantially since 1987, including with respect to:
 - (a) Communications (cell phone, internet, etc.)
 - (b) Other technology (digital and video cameras, etc.)
- c) The tools available for railroad bridge research are very different than those in 1987, including in terms of:
 - (a) Supercomputers and personal laptops
 - (b) Sophisticated analysis software and modeling kits
 - (c) Data collecting and data processing

As a consequence, a new workshop identifying current research needs for today and tomorrow is warranted for North American railroads. While a North American Workshop on Railroad Bridge Research Needs should be planned and organized, a survey of national experts on railroad bridges and structural engineering has been conducted in the meantime to best identify current topics for railroad bridges and structural engineering research.

2.2 Specific objectives of this survey-based study

The survey referenced in this report was conducted to achieve the following:

- 1) List research needs from different perspectives in the railroad bridge structural engineering field. Professionals from different areas, including consulting, contracting, railroads, and federal engineers, were contacted and surveyed to represent the diverse interests in the railroad community.
- 2) Identify the different importance levels of the research topics. The survey helped to determine the most important research areas from an overall railroad industry perspective, as well as for certain specific sub-groups.
- 3) Generate a list of research topics based on the relative importance given by the diverse population being surveyed. The potential research topics are sorted based on the interest shown by those interviewed, with the relative importance of the topics weighted and ordered. The resulting list shows the relative importance of the research topics according to the interviewees.
- 4) Discover new research topics that had not been identified in the initial set of questions provided. Through the opportunity for open-ended responses in the survey, new topics that were not previously considered are now listed as areas of potential interest for future research based on interaction with railroad bridge structural engineering experts.

2.3 Motivations for this 2010-11 survey

Additional reasons for conducting a survey to identify current topics for railroad bridges and structural engineering in 2010-11 include the following:

- 1) As listed in the attached references in this report, the design and construction of several railroad bridges during the last 10 years has been documented identifying the present and future needs for research (Moreu, 2007, 2008). Several particularities involving railroad bridge design, construction, and maintenance of railroad bridges were described in case studies that show a merging of new research topics related to railroad bridge engineering. This survey continues the work of merging research topics and forging new research areas with collaboration between academia, government, and the railroad industry.
- 2) Recent Structural Health Monitoring (SHM) studies of railroad bridge maintenance and replacement prioritization explore the potential of the use of wireless sensors by railroad bridge structural engineers in the study of their bridge structural integrity and performance under live loading (Moreu and Nagayama, 2007, 2008; Moreu et al., 2008). SHM tools, and particularly wireless sensors used for SHM research, have significantly evolved since their use in these referred studies. New generations of wireless sensors are easier to install and their cost is constantly decreasing. Advancing technology necessitates the research keep pace with new tools to maintain industry standards of safety.
- 3) There is increased attention towards railroad bridges today by several sectors of society, in part motivated by a high speed passenger rail plan (CNN, 2009). In addition, it is generally accepted that railroad transportation offers both economic and environmental advantages for society when compared with highway transportation. As a result, social awareness and receptivity towards railroads in North America has gained increased public attention. The timing of this survey takes advantage of this moment of public attention to increase awareness in the engineering community about railroad bridge maintenance needs.
- 4) Railroads have unique characteristics. Design, construction and maintenance of railroad bridges needs to be studied while understanding that railroads are private corporations. Privately owned and run infrastructures are built, maintained, and managed differently than public infrastructure. A specific study of the particular needs of railroads will benefit structural engineers interested in researching railroad bridges today.

An independent study towards current topics in railroad bridges and structural engineering is both justified and required to best address the particular and specific needs for research today in railroad bridges and structural engineering.

2.4 Description of the survey methodology

2.4.1 Survey methods and procedures

As explained in Section 2.2, this survey explores the main structural engineering research topics related to railroad bridges. To achieve this objective, the survey was conducted with the following considerations:

- 1) Based on their experience and perspective, experts in structural engineering and railroad bridges would be identified to explain today's research interests and necessary areas of emphasis. The selection of these experts is described later in Section 2.4.4.
- 2) A list of pre-selected topics would be presented to this group of experts to narrow their answers so that their input could be directed toward certain specific potential research areas. This group of experts would also be asked to provide their own suggested areas for research, allowing new topics to be included in subsequent interviews.
- 3) The format of the questions would be open to suggestions from interviewees so that the questions could be expanded to other areas during an interview. With this format, conversation and discussion with the interviewees about other research topics could be pursued.
- 4) In general, the interviews were arranged in the following sequence:
 - 4.1. An email was sent to the structural engineering expert to allow the interviewee time to review the topics and questionnaire in advance.
 - 4.2. A phone conversation appointment was scheduled between the interviewer and the interviewee. This format allowed conversation between the two parties and permitted clarifications that otherwise could be missed. Without this one-on-one conversation, misinterpretation and/or misunderstanding could arise. The phone interviews lasted from a minimum of forty-five minutes to multiple phone calls (sometimes three or four) lasting up to one hour each.
 - 4.3. When time and logistics allowed, a personal meeting was scheduled to clarify specific information after the interview. The author of this report personally met with fourteen of the sixteen structural engineers interviewed before or after the phone interview. These meetings allowed for deeper probing into additional aspects of the areas discussed. The one-on-one conversations also left room for personal feedback on specific topics of interest that were not included at the time of the phone conversation. These discussions allowed the researchers to collect new input about topics that came up during the year-long surveying period.
 - 4.4. Having multiple discussions with different engineers at various times during an entire year allowed for a variety of input from the population being surveyed. As explained above, the interviewing process incorporated new topics toward the end of the survey as more engineers had provided their own topics to the original list by that time.
 - 4.5. Over the course of the interviews (phone or personal), related literature (additional book or proceeding references) and/or new potential structural engineers were occasionally identified. This interactive process allowed

the researchers to incorporate additional experienced people in the survey beyond those originally selected, and helped assemble a broader representation of areas of interest, which then informed the final conclusions.

- 4.6. The content of the interviews were written and collected in a folder for each of the meetings. This way, each conversation was recorded, and could be used as a reference for future review and analysis in the report.
- 4.7. The findings were eventually sorted and listed in a reference table so that topics and inputs from each of the interviewees could be paired up with one another. For example, the responses are designated as “favorable” or “not favorable” when trying to select a topic defined as “researchable” or “of interest” for the railroad bridge structural engineering community.

2.4.2 Proposed research topics

Prior to actually interviewing the selected population, a list of proposed topics was preselected for the experts. With this defined range of interest, the focus of the survey could primarily be directed to those areas that had been collected previously from the railroad bridge structural engineering community.

This pre-selection was intended to:

- 1) Allow the contents of the survey to direct attention towards specific areas already identified as of importance for the industry.
- 2) Permit the experts to provide directions specifically towards these preselected topics.

The list of the main topics of interest did not restrict the topics discussed during the interview, but rather set specific goals to be discussed during a limited period of time. Additionally, a list of specific questions, consisting of a questionnaire about structural engineering and railroad bridges current research topics, became part of the survey items.

The list of preselected topics is presented in Table 2.1. The list of the survey questions is discussed in the next section of this report.

2.4.3 Survey questionnaire model

Along with the preselected topics listed in Table 2.1, a model for the questionnaire as presented in Table 2.2 was given to each of the structural engineers interviewed. This questionnaire combines open-ended questions with more specific items to be addressed. The survey model evolved during the interviews as structural engineers raised new questions over the course of the phone conversations that were not included at the beginning. These other topics identified in the middle of the interview process have been also included.

Because of this evolving survey format, some of the interviewees were only the original questions shown in Table 2.2, while others provided answers to the additional questions listed in Table 2.3. As discussed earlier, the author of this report has tried to follow up with those interviewees involved in the first stage of the interviews to include their insights to the topics listed in Table 2.3 that were not previously discussed.

Table 2.1. Potential research topics involving railroad bridges and structural engineering.

Topics	Description
Inspection and maintenance of railroad bridges: performance monitoring	Railroad bridge engineers need to quantify the capacity of their bridges. Which information would be best to collect? Which information has been historically collected / measured in the field? Is there a motivation for developing the applicability of wireless sensors for health monitoring of railroad bridges?
Railroad bridge inspections and engineering guidelines	How are bridges inspected today? Which structural engineering data is collected from bridges to decide if they must be replaced? Is there an interest to develop a “guideline” that structurally quantifies when structural components (slabs, piers, piles, etc.) need to be replaced / upgraded?
Longitudinal Force (LF) distribution in new bridge design	New bridge design currently underestimates the capacity of the track / rail for distributing the LF towards the abutments and overestimates the amount of LF actually absorbed by the intermediate piers. Might the determination of the actual LF carried by the substructure produce more efficient RR bridge designs?
High speed traffic on both existing and new railroad bridges	New tendencies in U.S. transportation policies will bring faster passenger loads (although lighter than freight loads) applied RR bridges. Does the MRE recommended practices cover the effects of these faster loads? How would these forecasted new loads impact the requirements for design, construction and maintenance of new railroad bridges? Examples from other countries’ current experiences could be included in this study.

All the interviewees received both the table of topics and the questionnaire. However, it should be pointed out that the conversations evolved differently with each of the engineers interviewed based on their professional areas of expertise. Nevertheless, these various emphases given by different experts clearly benefitted a more representative list of current research topics as finally collected throughout Chapters 3, 4, 5, and 6.

2.4.4 Description of the surveyed population

A list of people who were interviewed is shown in Table 2.4, along with some basic information about the qualifications of each individual. This list includes people from a broad spectrum of RR structural engineering exposure and responsibilities, so as to represent a wide range of views from the current population of professionals involved with the topic of this report.

The engineers interviewed represented a diverse spectrum of the current population of professionals dedicated to railroad bridge structural engineering in North America today. The following list shows the different categories of the selected population, and validates the diversity and variety of the interviewees in each of these categories:

Table 2.2. Survey questions about railroad bridges and structural engineering.

Survey questions
What are the main areas that take most of your time as a structural engineer for railroad bridges (differentiate: design, maintenance, repair, construction)?
What are the top three engineering concerns that you would be interested in a research program in civil engineering to study about your bridges?
What information would you like to know about the bridges you are responsible for?
How are railroad bridges structurally rated?
Specific questions
Would you be interested in knowing the actual displacement / acceleration of your bridges under traffic, if it could be fast and easy to get?
Are you worried about high speed trains crossing your bridges?
Do you have any Longitudinal Force (LF) concerns?
Are there higher load/cars – from 286,000 lbs/car [(130 metric tons)/car] to 315,000 lbs/car [(143 metric tons)/car] – concerns?
Any other suggestions / ideas?

- a) Years of experience: all levels of working experience were represented, ranging from engineers with as little as 4 years of experience in the railroad industry to the more experienced and experimented industry experts in RR bridges and structural engineering, with 50 or more years in this field.
- b) Role in the railroad industry: owners, consultants, and contractors are represented. Railroad bridge structural engineers working for the AAR and TRB are also included.
- c) Railroad category: railroad bridge engineers with experience in Classes I, II, and III participated in the survey. Amtrak engineers were also part of the survey to ensure that both freight and passenger concerns were covered. Four of the seven Class I railroads were included. Shorter lines were also represented.
- d) Areas of exposure: railroad engineers with different exposures throughout the various sectors of the railroad industry were included. There were other engineers who specialized in one sector throughout their entire career (design, construction, maintenance, or management). In this way, both general backgrounds and specialized knowledge were present.

Table 2.3. Questions added to the original survey.

Additional specific topics for questions
Current technology from track engineering that could be applied towards railroad bridge research and data collection
Bridge approach concerns
Long span bridges
Impact Factor (IF)
Fatigue
Seismic studies for railroad bridges
Finding damage in railroad bridges
Implementing Load and Resistance Factor Design (LRFD) in the MRE
Timber trestles
Change / update the E80 Railroad Live Load (E80) for design by a more precise loading input

- e) Areas of structural engineering and railroad bridge experience included, but were not limited to, the following: inspection, advanced design, steel, concrete, timber, monitoring, rating, management, safety, construction, replacement, and repairs.
- f) Experience with different railroads: engineers with diverse experience in different railroads were contacted for the survey, to include points of view from people who have seen different design, construction, and maintenance methods with various companies.
- g) Other structural exposure: some of the railroad bridge structural engineers taking part in the survey had diverse backgrounds from participating in other areas of Structural Engineering (SE) like buildings and highway bridge design and/or construction. This multiple exposure to different areas of SE benefits well-rounded answers and contributions to this survey-based study from a wider view of structural engineering as a discipline of service to the railroad industry.
- h) AREMA members and non-members were represented. AREMA memberships (including committee affiliations) are shown in Table 2.4. Under the AREMA Committee category, Not Applicable (NA) means not currently an active member of AREMA.

Table 2.4. Contacts list for the survey on railroad bridges and structural engineering topics.

Name	Job	Type(*)	Employer	AREMA Committee	License
Barrett, John	President	C	Bowman and Barrett	15	PE, SE
Byers, Bill	Director Structures	RR	BNSF	9, 15	PE
Carter, James	Chief Bridge Engineer	RR	NS	15	PE
Eschenbach, John	Sr. Project Manager	RR	Amtrak	11	A
Franz, Dave	Regional Engineer	C	OSMOSE	8, 10	PE, SE
Herbeck, Jeff	Bridge Supervisor	RR	BNSF	NA	EIT
Kleinshans, Danielle	Senior Engineer	C	CTL	NA	PE
Le, Hoat	Senior Engineer	RR	CN	NA	PE
Lozano, Don	Senior Engineer	RR	BNSF	10	PE
Manzanarez, Rafael	VP Engineer	C	T Y Lin	NA	PE, SE
Otter, Duane	Principal Engineer	AAR	TTCI	8, 9, 15	PE
Payne, Rich	President	C	ESCA Consultants, Inc.	8	PE, SE
Riehl, Bill	Senior Engineer	RR	RailAmerica	7, 24	PE
Scola, Sandro	Chief Bridge Engineer	RR	CN	7, 18	PE
Sweeney, Bob	Consultant	C	Modjeski & Masters	7, 15	PE
Unsworth, John	Chief Bridge Engineer	RR	CP	15	PE
Type(*)=	C – engineering, consultants or construction contractors; RR – railroads; AAR – American Association of Railroads.				

On the other hand, a few of the structural engineers interviewed brought very specialized formation in specific/individual areas of RR bridge structural engineering. These highly specialized contributions brought expertise to various topics of the survey that benefitted from the coverage of certain topics to a great level of detail. In this way, the input from professionals with a very specific high level profile were also included and taken into account in this report.

A description of the AREMA Committees to which each of the engineers belongs (in terms of actual membership) has been provided in Table 2.5. The license of each of the interviewees is included in Table 2.4, for which descriptions are given in Table 2.6.

Table 2.5. AREMA Committee description.

AREMA Committee number	Description
7	Timber structures
8	Concrete structures & foundations
9	Seismic design for railway structures
10	Structures, maintenance & construction
11	Commuter and intercity rail systems
15	Steel structures
18	Light density & short line railroads
21	High speed traffic
24	Education & training

Table 2.6. License description.

License initials	Description
A	Class A-general contractor
EIT	Engineer-in-training
PE, PEng	Professional engineer
SE	Structural engineer

Finally, a list of additional AREMA Committees related to the structural engineering railroad bridge community that were not listed in the conducted survey is noted in Table 2.7. Inclusion of these was not considered relevant for the exploration of current research topics for structural engineering and railroad bridges. The input collected from the

engineers belonging to the AREMA Committees listed in Table 2.5 should fairly represent the railroad bridge structural engineering community in North America. The AREMA Structural Functional Group is composed of Committees 6, 7, 8, 9, 10, 15, and 28.

Table 2.7. Other AREMA Committees not surveyed that are partially related to railroad bridges.

AREMA Committee number	Description
6	Building and support facilities
17	High speed rail systems
28	Clearances

2.5 Chronological sequence of the survey interviews

April 2009

The first step to prepare the survey-based study was to identify a list of potential main topics of interest in railroad bridges and structural engineering. The topics included in this list were gathered from the railroad industry, consultants having existing relationships with UIUC, various AREMA Committees, and other structural engineering publications and organizations. Secondly, preliminary research was carried out on these pre-selected topics and summarized in a short-brief report format. Thirdly, a literature review was conducted to identify current studies and challenges in these areas. Finally, a series of questions was developed to use during the survey along with the list of preselected topics.

To confirm the general interest and appropriateness of these topics and questions, a phone conference was scheduled with Duane Otter of the TTCI (AAR), in Pueblo, Colorado. The tables of topics and questions were discussed with Otter for finalization and prioritization, and were then used as a reference throughout the course of the actual survey. During this month, the list of potential experts on railroad bridges and structural engineering was also started (see final version in Table 2.4).

May 2009

Based on the phone conference with Otter, the list of pre-selected topics was modified and updated. Its final form was shown in Table 2.1. The final questionnaire model was modified to that shown in Table 2.2. The list of structural engineer interviewees was frequently updated during the course of the survey-based study; the final listing has been presented in Table 2.4. The list of topics and the questions listed in Table 2.1 and Table 2.2 were increased with new entries during the course of the survey, and those were collected in Table 2.3. As previously discussed, some engineers suggested additional research topics or questions during their interviews, and those new topics and questions were asked to the subsequent population of engineers being interviewed.

June 2009 to May 2010

The main core of the interviews and questionnaires were conducted during these 12 months. In most cases (fourteen out of the sixteen), a one-on-one meeting was held with the structural engineers interviewed. On these occasions, the topics that had been discussed over the phone were covered in much more detail with each interviewee. The main emphasis in this period of time was to contact this group of railroad bridge structural engineers exposed to research needs in the industry, and to collect their input on specific questions related to railroad bridges and structural engineering. A preliminary literature review was conducted on the topics suggested during the interviews.

May 2010 to June 2011

During the last year of the study, the findings of the survey were collected and organized. The conclusions were listed and recommendations were determined as a consequence of the survey. The survey and the findings were then compiled into a written report. Additional literature reviews were conducted, including, but not limited to: journal papers, conference papers, reports, textbooks, books, former published and private studies, and other selected publications. A few additional surveys not completed in the previous year were also conducted during this last year.

2.6 Selection, identification, and description of research topics

The main research topics identified by this study are listed in Chapters 3, 4, 5, and 6 of this report. The criterion for the selection of these topics was based on the following parameters:

1. Topics listed in the original list as shown in Table 2.1.
2. Topics as answered by the interviewees to questions listed in both Table 2.2 and Table 2.3.
3. Other areas of interest gathered from:
 - a. Suggestions by the interviewees during the interview process
 - b. Literature review suggested or identified during the survey
 - c. Related new topics identified by a combination of both (a) and (b)

In total, twenty-two different topics have ultimately been selected for inclusion in this report, as described in Chapters 3, 4, 5, and 6. These chapters gather the research topics under the following four categories:

- Design
- Management
- Maintenance & Construction
- Other Topics

Topics included in the design (Chapter 3) and management (Chapter 4) categories have both received a significant detailed coverage by the interviewees (mostly because these topics were included in the original topic description). Topics from these two chapters also received an in depth description in the literature and reference sections. All the topics in Chapters 3 and 4 have been described following the same structure:

- Background
- Definition
- Current Discussion

- Challenges for Research

Topics listed under the maintenance & construction category (Chapter 5), as well as those under the other topics category (Chapter 6) did not receive the same level of in-depth analysis in this report (mostly because they were proposed and included during the course of the interviews). Descriptions of these topics therefore have briefer sections than those from Chapters 3 and 4. Chapter 7 presents the overall results, and the conclusions of this study are described in Chapter 8.

Each topic listed in Chapters 3 through 6 belongs primarily to the engineering area under the title of the chapter in which they are listed. However, some topics could potentially be included in more than one chapter. The final inclusion in each specific chapter or category group (i.e. design; management; maintenance & construction; and other topics) was decided based on the main aspect of the relevant research area as it was discussed during the survey. The inclusion of each topic in one specific chapter does not necessarily ignore the fact that it could have been included in a different one if the survey and the conversations were presented with different emphasis.

Nevertheless, this current classification presents these topics listed and sorted from a structural engineering point of view. The current classification will assist readers in finding out more about specific research areas in railroad bridges and structural engineering, in part by making use of the Table of Contents located at the beginning of this report.

Finally, from the total of twenty-two topics, the six most outstanding areas of interest detected in the course of the interviews were picked out and sorted. These six main areas are shown in Chapter 7. They have been quantitatively classified, and their relative significance for research is shown at the end of this report, along with general conclusions and future recommendations (in Chapter 8).

Chapter 1 of this report presented an overview of railroad bridges in North America, including a description of the main institutions affiliated with railroad bridge research as well as past research work related to railroad bridge structural engineering. Chapter 2 described the objectives, motivations, methods, and procedures of the survey-based study. This study has identified the main railroad bridge structural engineering research topics in North America today. Chapters 3, 4, 5, and 6 of this report will present the different topics identified as a result of this survey-based study.

These four chapters will show the reader the complexity surrounding railroad bridges in North America. The description of the research topics in these four chapters will show that areas of design, management, maintenance, and construction interact within each other in the case of North American railroad bridges. This is due to the fact that the replacement of railroad bridges is one of the main duties of railroad bridge departments in North America today. During the process of a railroad bridge replacement, all areas (design, management, maintenance, and construction) must be correctly understood and combined. The reader should remain aware of the level of importance of bridge replacements within the North American railroad industry when reading the following four chapters.

Figure 2.1 shows the different steps during a railroad bridge replacement. As in many railroad bridge replacements, this project combined new design construction with existing bridge elements maintenance, in addition to current (and future) bridge management. From left to right, top to bottom the images in Figure 5 show the four steps

during construction: (1) Existing timber trestle view from the southeast end of the bridge to be replaced under current traffic. Traffic cannot be stopped during the bridge construction until the superstructure replacement takes place. Existing DPGs (two spans) located north of the timber trestle will remain after the timber replacement. New steel piles have been driven between the timber piles. These new steel piles will carry new DPGs. (2) East view of the timber trestle prior to the superstructure replacement. Two cranes used for the lifting of the new superstructure prepare the lifting operations. A new DPG can be seen between the old bridge and the camera. (3) Traffic is interrupted for 60 hours. The old timber trestle is completely removed. The first DPG is placed on top of the new steel pile concrete pier caps. (4) All four DPGs are in place, along with a new concrete span. Traffic is back on the bridge. The final view of the new bridge contrasts with the remaining timber piled at the job site. The old timber members will be cleaned and removed as waste by the railroad contractor forces.



Figure 2.1. Railroad bridge trestle replacement using several DPGs in North America.

RAILROAD BRIDGE DESIGN

3.1 Introduction

The following seven topics listed below are current concerns of the railroad community related to railroad bridges design. All these seven topics have been identified of significant importance by the audience interviewed. They are included in the design category since the aspects discussed during the interview mostly focused in areas pertaining the design phase of railroad bridges. However, it is acknowledged that these topics also have direct effects on other areas, such as railroad bridge management, maintenance, and construction. Therefore, relevant features of bridge management, maintenance, and construction not necessarily directly related to the design phase of railroad bridges are also covered in each of the seven topics described in this chapter.

The seven topics included in this category are:

- Longitudinal Force (LF) distribution
- High Speed Rail (HSR) traffic
- Long span bridges
- E80 design load
- Bridge approaches
- Impact Factor (IF) in railroad bridges
- Effects of transitioning from 286,000 lbs/car to 315,000 lbs/car

The length and depth of the discussion provided for each topic depends on both the research literature consulted and the levels of emphasis given by the engineers surveyed. While most of the current design codes discussed refer to the MRE recommended practices, there are other reference materials available that can help researchers to become more familiar with the current topics involving the design of railroad bridges. An example is the book *Design of Modern Steel Railway Bridges* by John Unsworth. This book covers the design of railroad bridges as a different entity from other types of bridges or structures. Throughout his book, Unsworth collects the recommended practices from MRE Chapter 15 and combines them with key steps involving the design and maintenance of steel railroad bridges (Unsworth, 2010). This is one of the only pieces of current specialized literature covering the structural engineering design of new railroad bridges.

The production of specialized publications in railroad bridge structural engineering design is in high demand and can benefit current educational and research demands from the railroad industry.

3.2 Longitudinal Force (LF) distribution

Background of the longitudinal force effect in railroad bridges

Since 1996, numerous studies carried out by the AAR have been demonstrating that the longitudinal forces transferred to railroad bridges were much higher than what would

have been expected or determined by AREMA Manuals (Uppal et al., 2001). Numerous studies in the last decade credited this increase to a diverse range of reasons. According to Sweeney and Suthon (2002), some of the conclusions obtained in studies from the 1960s (AAR, 1966b; Sanders et al., 1960) were based on testing programs that did not cover the maximum longitudinal force available at that time, so low LFs were recorded (Foutch et al., 1997; Otter and Sweeney, 2001). These same studies stressed how new machinery and equipment in the railway network generates up to twice the tractive effort of older locomotives (Foutch et al., 2006) and longitudinal forces up to 25 times what the MRE predicted (Foutch et al., 1997).

Definition of longitudinal forces effects for railroad bridges

Figure 3.1 shows the theoretical longitudinal force associated with the force of breaking or accelerating (Unsworth and Payne, 2006). The bridge will resist the LF even before the train arrives at the actual bridge location.

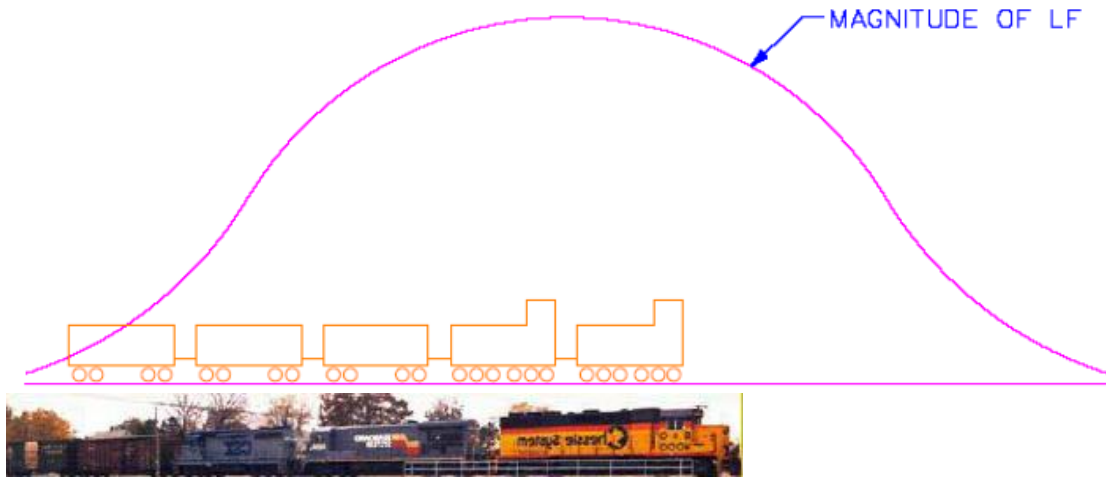


Figure 3.1. LF distribution over a railroad bridge (Unsworth and Payne, 2006).

Today, Chapters 8 and 15 of MRE (AREMA, 2009) define the longitudinal force to be computed as the worst of the following:

$$LF_B(kips) = 45 + 1.2L$$

$$(LF_B(kN) = 200 + 17.5L)$$

$$LF_T(kips) = 25\sqrt{L}$$

$$(LF_T(kN) = 200\sqrt{L})$$

Where:

- LF_B= Longitudinal Braking Force
- LF_T= Longitudinal Traction Force
- L= Length in feet (meters) of portion of bridge under consideration according to MRE 8.2.2.3.j.1 and MRE 15.1.3.12.a, for concrete and steel, respectively (AREMA, 2009)

These are the E80 loads (see section 3.4). For other loads different than E80, these values should be scaled adequately.

Discussion of current concerns involving the longitudinal force

The MRE currently presents the same definition for L in both steel and concrete bridge superstructure design chapters. It also includes this definition for the design of railroad bridge substructures. Currently, the statement “portion of bridge under consideration” allows different interpretations. Whereas for superstructure considerations, L could be chosen as the span under study, substructure analysis needs to account for bridge segments up to the entire length of the bridge. AREMA is currently developing a revision to the definition of L that will address the differences between each case. Since the computation of the longitudinal load depends largely on the definition of L, and AREMA continuously develops and implement past and current research regarding LF, it is clear that this topic is of current interest for research and study by the railroads in North America.

On a related topic, Chapter 8 of the MRE defines the distribution of the longitudinal force to the substructure taking into account the relative stiffness of each pier (AREMA, 2009; Unsworth and Payne, 2006) (see Figure 3.2 illustrating two bents with different stiffness). To design railroad bridge foundations properly for longitudinal force considerations, a fuller understanding of the railroad bridge foundation systems used in railroads is in order.

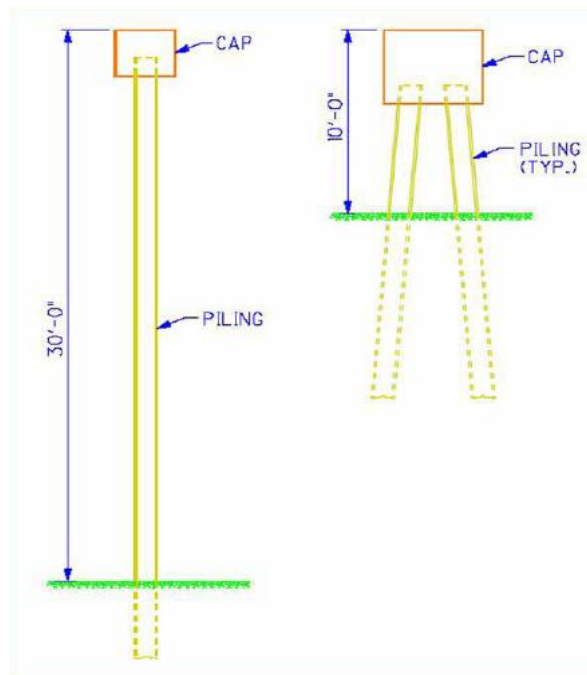


Figure 3.2. Bents models with different relative stiffness (Unsworth and Payne, 2006).

Extensive research in the 1960s and 1970s covered the modeling and understanding of how the longitudinal force was being resisted by railroad bridges (AAR, 1964, 1965). Additionally, railroad bridges and structural engineering publications often refer to

studies on deep foundations and lateral loading capacity. These studies are widely published by experts in both structural and geotechnical engineering interested in the modeling and understanding of railroad bridge deep foundations for LF considerations. References included past work in this area by Davisson with other authors (Alizadeh and Davisson, 1970; Davisson and Gill, 1963; Davisson and Robison, 1965; Davisson et al., 1970; Davisson et al., 1983) or Broms (Broms, 1965).

The significance and importance of LF in the design of new railroad bridges was also studied and compiled by private consulting reports (Dooley, 1999; Payne, 1998, 2003). Additionally, given the importance of timber trestles today in North American railroad bridge networks, timber piles and their lateral load capacity have been modeled and addressed (Armstrong, 1979). Finally, the effects of continuously welded rail in the longitudinal force distribution has recently been modeled and studied in Europe (Ruge, 2007).

Based on this evidence, today there is an interest in developing research topics related to the testing, validating, and modeling of LF on railroad bridges.

Challenges identified in longitudinal forces effects in railroad bridges

This survey-based study identifies the following structural engineering research challenges and opportunities related to the effects of LF on railroad bridges:

1. Numerous railroad engineers stressed how the actual value of the LF captured by the AREMA formulas had been extensively tested by the railroad community, specifically at the TTCI (AAR) facilities in Pueblo, Colorado.
2. Some of the most experienced railroad bridge structural engineers in North America surveyed in this study pointed out that research has shown that the LF was not carried to the embankments off of the bridge under HAL; but it all went to the substructure, without any dissipation through the track, according to extensive testing and analytical studies carried out by AAR and collected by researchers, including Foutch et al. (1997), Otter and Sweeney (2001), and Foutch et al. (2006).
3. Even when the consultant engineers interviewed did not consider LF to be of a high priority, the majority agreed that further studies could refine the current LF knowledge. This future work could confirm the results obtained by TTCI (AAR). Some of the bridge engineers working for the railroad suggested the development of computer models for this purpose.
4. Another potential research topic associated with the longitudinal force identified was to measure the capacity of backwalls to absorb LF in cases where the structure has fixed bearings at the abutments. The California DOT (Cal Trans) criterion for seismic loads in highways has traditionally been used for this purpose. However, there are two reasons to develop an specific study towards railroad bridges in this case, to know:
 - a. Different geometries between highways and railroads.
 - b. Differences between seismic loads and longitudinal forces.

This same group of engineers proposed developing laboratory experiments with different soil types along with full size push tests and field measurement campaigns.

5. A significant portion of the consulting engineers involved in the design of new railroad bridges stressed how the current formulas shown in the MRE can be too restrictive. In particular, structural engineers pointed out that the MRE may be overestimating longitudinal forces that are actually acting on the bridge, and other railroad engineers working for the carriers agreed with their assessment. Currently, the MRE allows a maximum of 1” displacement under LF. This criterion generally governs the design of deep foundations for railroad bridges as ruled by the MRE. However, greater overstresses are permitted for seismic than for LF. It is suggested by design structural engineers that a probabilistic study could be incorporated for LF as it is used for seismic analysis (Unsworth and Payne, 2006).
6. Railroad bridge managers interviewed considered the research already conducted at TTCI (AAR) to be sufficient and noted that new studies related to LF would not be a top priority today; at the very least, they prioritize other urgent topics. In summary, this group of bridge engineers working for railroads trusts the studies already undertaken at TTCI (AAR).
7. Finally, some of the Class I engineers explained how they are currently handling the unknown load distribution by adding a better anchorage to their bridges. On the contrary, Class II and III railroad engineers clarified how this is not a concern with short lines. As they explained during the course of the interviews, short lines do not carry the load down from the track to the bridge at all. This is primarily due to the lack of anchorage inherent to railroad bridges in these shorter lines.

It can be summarized from this study that most of the interviewees did not consider the longitudinal force to be a pressing topic for research today. The main reason behind this generalized opinion rests in the fact that previous studies were undertaken during past decades, whereas new research topics are currently unknown although contemporary research and studies should be directed to these current topics.

3.3 High Speed Rail (HSR) traffic

Background of the HSR in the U.S.

According to popular U.S. media (CNN, 2008), Federal and State Governments have joined both efforts and funding to develop a new national network of high speed passenger rail in the near future. In addition to the \$1.3 billion already dedicated towards Amtrak, the Obama administration envisions changing the way Americans travel for distances from 100 to 600 miles apart. On January 27, 2010, President Obama announced more than \$8B in funding from the FRA to begin the construction of high speed railroads (Yonah, 2010).

In recent years, private initiatives have lobbied to make high speed passenger railroads a reality in the U.S. For example, the Midwest High Speed Rail Association (MHSRA) recently published the document entitled *Saint Louis to Chicago in Two Hours by 2016* (MHSRA, 2010a). Figure 3.3 shows the vision for the Midwest Corridors as seen by the MHSRA in comparison with already available HSR networks in Europe and Asia, respectively (MHSRA, 2010b).

According to sources such as the MHSRA, the HSR would bring many benefits to the American society, including, but not limited, to:

- a) Environmental benefits (cleaner transportation)
- b) Closeness to users
- c) Efficient communication system
- d) Economic stimulus (job creator)

In March 16, 2010, at the AREMA Board of Governors meeting, AREMA decided to lead the development of HSR in the U.S. (AREMA, 2010).

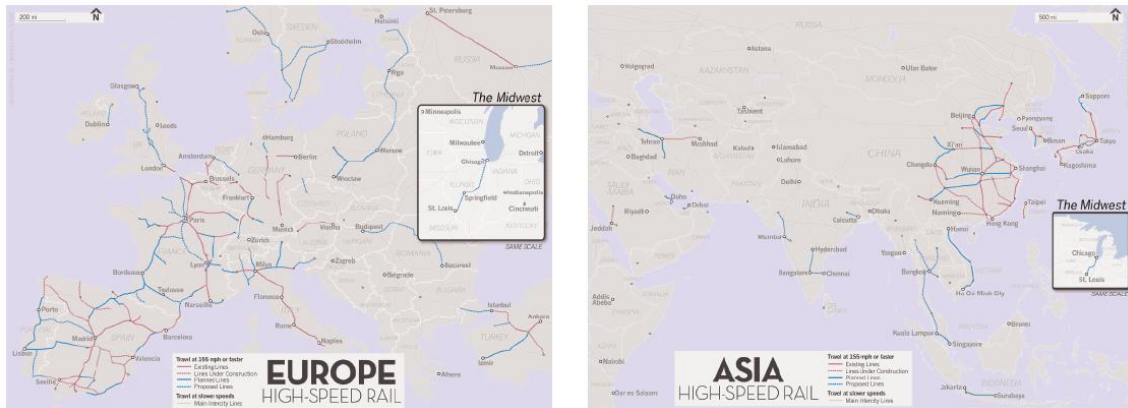


Figure 3.3. MHSRA Vision for North America in comparison with Europe’s and Asia’s current HSR network (MHSRA, 2010b).

However, the current RR infrastructure design recommended practices for bridge design do not cover “high speed” effects. This is because, as of today, there have not been past high speed experiences or a pressing need for their development. It is worth noticing that the effects of high speed in bridges would not only impact the design phase, but also other related aspects such as bridge maintenance and inspection requirements, to name just a few.

North American engineers need to study, review, and properly upgrade current recommended practices to ensure that safe and reliable bridges will be able to carry the new speeds being discussed. The following section will define what the new high speeds under consideration are.

Definition of HSR

The interviewees pointed out that HSR should be defined prior to discussing its effects on railroads in general and railroad bridges in particular. To define HSR values and meanings, current FRA operating speed limits were consulted. An FRA table listing their values and nomenclature is provided in APPENDIX C at the end of this report (FRA, 2009). The FRA currently lists nine different Classes of track based on the allowable operating speed, ranging from Class 1 to 9 (slowest to fastest). In the FRA table, Class 9 track limits the allowable operating speed less than 200 Miles per Hour (MPH) (320 Kilometers per Hour (KPH)). However, California’s former Governor Arnold Schwarzenegger recently made public the California High Speed Plan with speeds up to 220 MPH (350 KPH) (Schwarzenegger, 2010). The new high speed of 220 MPH (350 KPH) is not included in the referred FRA’s track classification.

Up until very recently, North American society had identified 110 MPH (175 KPH) with high speed railroads, since this has traditionally been the velocity pursued by the Federal Government when targeting HSR (please read clarification about HSR for the U.S. in the following section). It is worth pointing out that, independently of the final definition for high speed, nowadays the passenger operating speed in most Class I railroads falls under 79 MPH (125 KPH). It is accepted by the interviewees that today any speed exceeding 90 MPH (145 KPH) falls into the HSR category, although there is not a standard developed in this regard yet, and this concept is constantly evolving.

In addition to the current definition for HSR, this report proposes a new clarification of the high speed concept, which is described in the next section along with associated pressing research topics.

Discussion of topics involving HSR and railroad bridges

This survey-based study has identified up to ten structural engineering concerns related to high speeds in railroad bridges that should be studied. Two different HSR categories in the U.S. imply two unique groups of problems. These two groups of railroad bridge issues would need to be studied separately:

1. Existing/new railroad bridges that would need to be upgraded to support higher passenger speeds for the HSR corridors carrying passenger traffic up to 110 MPH (175 KPH). These bridges would be sharing passenger traffic with freight traffic.
2. New bridges that would accommodate speeds up to 220 MPH (350 KPH) as proposed by former Governor Schwarzenegger (California High Speed Rail Authority, 2010). These bridges are exclusively for HSR passenger trains.

Consulting structural engineers proposed studying the two cases separately. In their own words, they want to emphasize that case (1) should not be included under the HSR case. In particular, they proposed the terms for case (1) of either “Increased Speed Rail” or “Intermediate Speed Rail” (ISR). The main motivation for their distinction was to avoid confusion with the worldwide accepted concept of HSR passenger trains over 200 MPH (320 KPH). They wanted to use worldwide terminology to refrain from misleading international readers.

During this study-based survey the main emphasis was given to the first case (ISR), although current general HSR discussions in North America still do not make a point to clearly separate ISR and HSR scenarios from each other, as shown earlier in this report.

The following section lists current research concerns or challenges related to railroad bridges under both ISR and HSR categories. The research challenges listed in the next section concern the effects of “higher” speeds in railroad bridges in U.S.

Challenges identified related to railroad bridges under HSR traffic

This survey-based study identifies the following structural engineering research challenges and opportunities related to the effects of high speed traffic in railroad bridges:

1. Chapters 17 and 18 of the MRE recommended practices deal with high speeds. However, they do not address bridges and structures from a structural design point of view. A new chapter or section(s) could be developed and

made available which would specifically deal with structures and bridges under HSR traffic.

2. Some Class I RR bridge engineers suggested studying and expanding the contents of AREMA Chapter 15 (steel structures). According to them, steel decks and deck fasteners are not designed for HSR, so new standards should be developed. They further explained that steel bridges designed under the current recommended practices considered a maximum speed of 80 MPH (130 KPH) for freight and 90 MPH (145 KPH) for passenger trains (for current Class 5 track categories, please refer to APPENDIX C at the end of this report). To run faster traffic, supplementary requirements should be developed and proposed in the near future to replace current recommended practices.
3. According to some bridge engineers working in Class I railroads, ballasted deck bridges carrying HSR traffic exceeding the speed limits of track Class 5 would be of special concern. On the contrary, different railroad bridge engineers suggested that the main problems adapting the existing infrastructure to HSR would be focused in the surfacing and track elements (ballast, ties, and anchor plates) rather than in the actual bridge structures.
4. Consulting engineers in charge of new bridge design and maintenance suggested studying new track geometry and tolerance limits for HSR conditions within Chapters 7, 8, and 15 of the MRE. Lateral loads for cases exceeding these speeds would also need to be checked and re-defined. Finally, according to other railroad and consultant bridge engineers, deflections requirements in the current AREMA recommended practice section (1/640 for simple spans of both concrete and steel beams) would also need to be upgraded to match indexes proposed in other countries (1/4000 in both France and Japan).
5. Class I structural bridge engineers stressed the importance of limiting the IF in the track that could be derived from an increase of the speed. They recommended studying any other IF effects that could be transfer to the rails, which the current track may not be designed to handle. Past negative experiences in the United Kingdom when adopting current track for an upgraded speed shows the risks of adopting higher speeds on existing infrastructure (Carr and Greif, 2000).
6. Research shows an increasing interest in the last decade towards dynamic analysis of bridges under moving loads, due to the proliferation of HSR along with ongoing efforts to upgrade existing railroad infrastructure (Majka and Hartnett, 2008). Consultant engineers stressed the need for vibration studies to develop new limitations in the design of structural members that will be affected by vibrations in the 1 to 80 Hz range, such as railings and other attached structures to the bridge elements.
7. According to some opinions collected in the survey, Class I railroads and other potential high speed carriers think that the North American system includes a large number of crossings on grade, which would not allow HSR traffic from a structural maintenance point of view. Rail crossings at these speeds are not practical, and the way railroad intersections are designed today

would defeat the HSR purpose. From their perspective, an entirely new railroad infrastructure would govern the design of track and bridges for HSR.

8. RR bridge structural engineers working in railroads from Classes I, II, and III all agreed that short spans today cannot adapt to carry high speed traffic (especially existing timber trestle bridges).
9. Past studies in Europe encourage the study of HSR bridges by means of dynamic monitoring of their response under ambient vibrations (Cremona, 2004). In this spirit, new HSR bridge maintenance strategies could incorporate advanced monitoring techniques to assess their performance for the railroads throughout time.
10. Class I RR structural engineers stated that upgrading RR bridges for higher speeds would only be a good research topic if it were studied in parallel with the upgrading of the track. In their opinion, upgrading RR track for HSR requires more efforts in terms of budgeting and coordination than other conventional railroad bridge operations.

In summary, structural engineers did not find this to be a top pressing issue in general, based on current demands from the railroads in North America. However, the majority found the topic of interest from a research point of view. They concede that the interest of this research would increase if or when HSR is given priority by clear initiatives that would justify their study and research.

3.4 Long span bridges

Background of long span railroad bridges

As presented in Section 1.1 (Motivations for this study) and Section 1.2 (Introduction to railroad infrastructure philosophy), railroad networks must be maintained to keep the railroad industry safe and financially profitable. According to railroad bridge managers, maintenance costs associated with bridge repairs, upgrading, and strengthening become excessive when the frequency and/or extent of the repairs exceed values that would have made the replacement of the old structure by a new one more economical for the owner. Railroads maintain their bridges in service as long as (a) they can safely operate and (b) their maintenance costs relative to safe operations are kept under reasonable margins.

In this scenario, the replacement of a steel truss bridge over a large river such as the Mississippi will be delayed until the current bridge cannot take any additional load safely, because the maintenance costs are relatively minor compared to the large investment that would be required for replacement of the entire bridge. This means that the majority of medium- and long-span bridges used on North American railroads today are over 100 years old.

When these bridges were built, the tools and technology of the era governed the design and construction of their spans and proportions. Many structural engineers pointed out that structural engineering design and construction powers have dramatically evolved since then. Nevertheless, these long span bridges built 100 years ago have worked well until today because Class I railroads have kept long span bridges safely operational by continuously investing in maintenance.

According to Otter, some American bridges over 120 years of age are getting close to the end of their expected life of service. The design and construction of replacement

bridges will take place within the next few decades. New long span railroad bridges were targeted for replacement under projects funded with the Obama administration's stimulus package in 2009 and have since been upgraded (Allen, 2009).

Finally, the long span railroad bridges are shorter than long span highway bridges. This is primarily (but not solely) because RR live loads are higher than highway live loads.

Long span bridges are less likely to attract global attention because the length of railroad spans cannot match those of highways. Nevertheless, readers should be reminded that railroad bridges pioneered the bridge industry in North America over 130 years ago. Since then, RR bridges have achieved spans as long as 1800 ft (0.36 miles) in the case of Quebec Bridge, near Quebec City, Quebec, Canada. The international engineering community today considers the Quebec Bridge a major engineering landmark for having such a lengthy main span.

Definition of long span bridges for railroads

According to experienced railroad bridge structural engineers, long span railroad bridges are those that include at least one "long span" – a distance over 0.6 miles (or in excess of 1 Kilometer (KM)) – throughout their entire length. The span length is the distance measured between two consecutive piers.

However, according to railroad engineering practicing standards, existing bridges crossing major rivers in the United States whose main spans exceed 500 ft (152 m) have been traditionally referred as long span bridges, and will be so called in this report. For illustrative purposes, Figure 3.4 shows a view of the Cairo Bridge over the Ohio River. The longest truss of this bridge spans 520 ft (158 m). This bridge was originally built in 1889, with its superstructure replaced in 1951 (Modjeski and Masters Engineers, 1953).

Current topics of discussion involving long span bridges for railroads

The structural engineers interviewed pointed out the following discussion topics related to long span railroad bridges in North America:

1. Railroads and highway bridges carry very different loads. Their service conditions also follow different requirements, as it was shown in Chapter 2. As a consequence, railroads have unique characteristics that generate new challenges in the long span railroad bridge engineering community. Railroad bridges with long spans should be studied differently than long span highway bridges.
2. The forecast of loads and capacity demands in the railroads will affect the performance of existing long span bridges in North America and, consequently, their maintenance. Traditionally, long span bridges have been maintained by the railroads annually. Small periodic investments towards the maintenance of these trusses were justified to avoid the major capital required to replace a structure over 130 years old.
3. Year after year, maintenance costs increase with the age of the structure. In addition, loads and traffic frequencies also increase. These new demand levels may exceed tolerances and eventually affect the bridge capacity. As a consequence, according to railroad bridge structural engineers in charge of research, the next decade could bring a change in the maintenance policy for

existing long span bridges. In the near future, new long span bridges may be designed and built to replace existing railroad bridges in North America.

4. According to both railroad engineers and contractors, during last few decades, highway bridge structural engineers have developed new technology towards long span bridge design and construction, which has paved the way for the railroad bridge industry. Now that the life of long span RR bridges may be close to their expiration date, the successes of the highway bridge community can be implemented by the railroads.
5. In this same philosophy, existing light rail long span bridges from around the world can be used to set basic references for developing a long span approach for freight railroads. Examples of long span light rail bridges suggested included the Orinoco Second Crossing (completed in 2006 in Venezuela) and the Tsing Ma Bridge at Hong Kong (Wong, 2004).
6. Finally, other engineers suggested studies investigating more specific cases, like the effect of continuous welded rail on a suspension bridge, which reported deflections of 17 ft (5 m) at the center of a 7,475 ft (2278 m) long continuous truss (Rao and Sanghvi, 2000), or work developed in the Huey P. Long Bridge (Kleinshans, 2008).



Figure 3.4. Cairo bridge over the Ohio river between Illinois and Kentucky.

Challenges identified with long span bridges for railroads

This survey-based study identifies the following structural engineering research challenges and opportunities related to long span railroad bridges:

1. According to some of the structural engineers in charge of design and maintenance of bridges, design loads will need to be upgraded in order to

- efficiently design new long span bridges. (Please see section 3.4 for further discussion about this subject).
2. Similarly, the deflection/span ratio restrictions would need to be revised. According to some structural bridge engineers, the existing (1/640 deflection/span) limit is “too liberal” and would not address a realistic long span design scenario. This same group of experts suggested learning from existing regulations across the Atlantic and Pacific Oceans (Eurorail in the European case; and related codes for the applicable Asian countries, respectively).
 3. The same group of structural engineers proposed new studies about slope and rotation changes in long span railroad bridges under live load. Rao and Sanghvi have documented (a) a maximum of 0.12% change in grade and (b) any vertical curve not sharper than 13,124 ft (4000 m) radius as the adequate criteria for speeds of 38 MPH (60 KPH) (Rao and Sanghvi, 2000).
 4. According to railroad bridge engineers with experience in new steel design and maintenance, research should study fatigue considerations in suspenders and cables for cable-stayed bridges. (Further discussion on fatigue for railroad bridges is included in section 6.6.)
 5. Railroad bridge structural engineers with experience in the consulting field suggested new research directed to the instrumentation and monitoring of long span railroad bridges. Wong carried out work on this topic in Hong Kong (Wong, 2004). This topic is also covered in Chapter 4 (field inspections, bridge instrumentation) and Chapter 5 (prioritization of member replacement, robustness of bridges, and current practices to extend their life).
 6. According to railroad bridge engineers, multidisciplinary efforts will be required for the design of new long span bridges under HAL. The disciplines would include, but be not limited, to mechanical engineering, electrical engineering, material engineering, and structural engineering. These studies for long span bridges would include fatigue, impact, dynamics, and other traditional structural engineering topics under the perspective of the long span bridge scenario. Dynamic interaction between the running trains and the long span bridges should also be studied. Past studies include modeling work and results for suspension bridges and passenger trains (Xia et al., 2000).

3.5 Cooper E80 Railroad Live Load (E80)

Background of the E80 Cooper design load

The MRE recommended practices list RR bridge design loads for each specific bridge type (see Table 8 for descriptions of AREMA Committees) (AREMA, 2009). Each chapter explains the values and combinations associated to each loading case acting on a railroad bridge. For example, Chapter 8 in AREMA should be counted in order to design a new reinforced concrete (RC) railroad bridge.

To calculate the dead loads acting on an RC railroad bridge, Chapter 8 of the MRE provides the following values (AREMA, 2009):

- Track, rails, inside guardrails and fastenings 200 lbs per linear foot of track (3kN/m)
- Ballast (including track ties) 120 lbs per cubic foot (1900 kg/m³)
- RC 150 lbs per cubic foot (2400 kg/m³)
- Earth filling materials 120 lbs per cubic foot (1900 kg/m³)
- Waterproofing and protective covering Estimated weight

The MRE recommends the use of the E80 Cooper as the live load for the design of new railroad bridges. Since structural engineers who do not work with railroad bridges traditionally do not know the E80 Cooper load, the definition of the E80 Cooper load is provided in the next section, followed by a historic background of the Cooper load along with current discussions about its use today for railroad bridge design.

Definition of the E80 Cooper load

According to Chapter 8 of AREMA (AREMA, 2009), the recommended live load for each track of main line structure is Cooper E80 (EM 360) loading, which represents the load of two Consolidation-type steam locomotives with trailing cars (Unsworth, 2010). The same load is used for the design of both timber bridges (AREMA Chapter 7) and steel bridges (AREMA Chapter 15) (AREMA, 2009). The spacing and values for these loads are the same for each bridge type (shown in Figure 3.5).

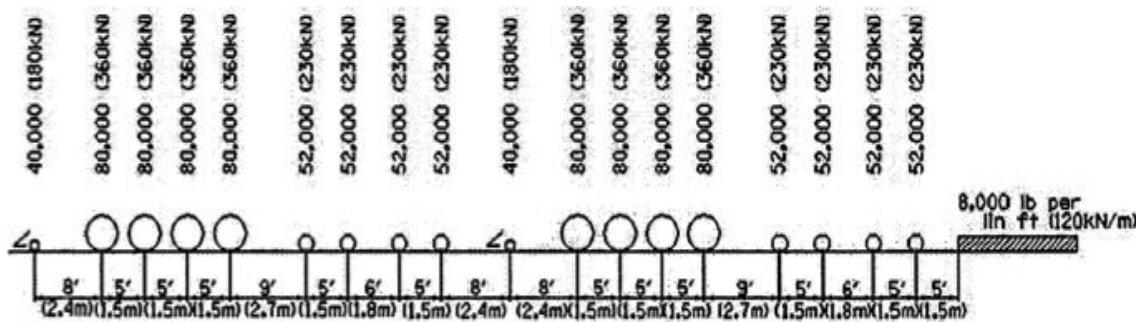


Figure 3.5. Cooper E 80 (EM 360) axle load diagram (Figure 8-2-1) (AREMA, 2009).

MRE recommends an alternative live load composed of four consecutive 100,000 lbs (45 metric tons) axles for shorter spans (AREMA, 2009). The spacing between these applied loads is 5, 6, and 5 ft (1.5, 1.8, and 1.5 m). However, this report solely discusses the definition and use of the E80 Cooper live load by North American railroads. The topics uncovered during this research are related to the use of the E80 Cooper design load by North American railroads today.

Discussion on E80 design load for railroad bridges

North American railroads recommended design practices first adopted the Cooper load in 1905. According to Unsworth, this was the first general structural design code for steel bridges in the United States (Unsworth, 2003). However, the Cooper load history goes back even earlier. Theodore Cooper formally presented his Cooper load proposal in 1894 to the American Society of Civil Engineers (ASCE) (Cooper, 1894). Further discussion about the evolution of Cooper loading is available in the study “The History and Development of Cooper Railroad Bridge Loadings in America” (Higgins, 1994). In addition, Cooper described the effects of live loads in railroad steel bridges in his prior publication “General Specifications for Steel Railroad Bridges and Viaducts” (Cooper, 1901). See Figure 3.6 below.

The Cooper load provoked some discussion among the interviewees. In the first place, the group clarified that the loading pattern shown in Figure 3.5 is an old standard that does not apply to today’s diesel engines. However, according to different engineers surveyed in this study, it has proven to be a good, conservative value for the design of railroad bridges. This group of engineers reasoned that evidence has proven that the E80 loading has been effective for designing bridges since bridges have successfully adapted to safely carry changing loads for over 100 years.

According to this reasoning, the vast majority of the engineers stated that today there is not a pressing desire in the industry to replace this loading pattern with a new one. These engineers clarified that railroads would be unlikely implement a new load design without proven performance evidence. An unproven loading pattern could not compete with a standard that has functioned well for a long period of time, even if, as they acknowledged, the current approach is understood to be quite conservative. Most interviewees foresaw little interest by the structural engineering railroad bridge community in replacing the Cooper load formula, especially structural engineers involved in railroad bridge construction.

However, other interviewees expressed their interest in developing a more precise live load expression for the railroad bridge industry. For example, they stated that long span bridges could be designed under more realistic live loads, although they also made clear that this approach should always be reserved for particular bridges, and only used on one-on-one design basis.

They clarified that today specific situations justify modifying the E80 Cooper load as described in the MRE. To obtain specific information regarding bridge responses, it is common to use live loads such as E92 or E120 in the design and/or the analysis phase. For these cases, the same spacing between the concentrated loads shown in both Figure 3.5 and Figure 3.6 is kept. However, the load is scaled by $92/80$ and $120/80$, respectively. It can be said that today’s practice refrains from new ways of modeling and estimating railroad bridge live loads other than by using the Cooper load.

Consulting engineers did justify the use of different live loads like E92 or E120 when trying to obtain different answers (i.e., performance under certain limit states) in the design phase or analysis of railroad bridges. These specific situations justify modifying the E80 loading described today in AREMA. As previously discussed, it may be difficult to present a new way of modeling and estimating the live load because the E80 reference is still acceptable for use.

Recent railroad bridge research tested the capacity of 100-year-old concrete beams under E80 loading (Szkolka and Banas, 2006). These experiments tested the capacity of three beam elements subjected to static loading. The results showed a flexural capacity up to four times the designed E80 Cooper load, after 100 years of uninterrupted service. These tests show that additional research investigating better understanding of current loadings, particularly research comparing design loads to real demand loads, can benefit the railroad industry.

Class.	STANDARD TRAIN LOADINGS.														Uniform Load.				
	Distances in feet.																		
	8	5	5	5	9	5	6	5	8	8	5	5	5	9	5	6	5	5	
E 27	13500	27000	27000	27000	27000	17550	17550	17550	17550	13500	27000	27000	27000	27000	17550	17550	17550	17550	2700 lbs. per lin. ft.
E 30	15000	30000	30000	30000	30000	19500	19500	19500	19500	15000	30000	30000	30000	30000	19500	19500	19500	19500	3000 lbs. per lin. ft.
E 35	17500	35000	35000	35000	35000	22750	22750	22750	22750	17500	35000	35000	35000	35000	22750	22750	22750	22750	3500 lbs. per lin. ft.
E 40	20000	40000	40000	40000	40000	26000	26000	26000	26000	20000	40000	40000	40000	40000	26000	26000	26000	26000	4000 lbs. per lin. ft.
E 50	25000	50000	50000	50000	50000	32500	32500	32500	32500	25000	50000	50000	50000	50000	32500	32500	32500	32500	5000 lbs. per lin. ft.

Figure 3.6. Cooper load for railroad bridges (Cooper, 1901).

According to this survey-based study, the results of this research would assist in determining better ways to relate the structural capacity of railroad bridge elements in comparison to the loading demands under train traffic. This and other related potential research topics related to the E80 Cooper loading are listed in the next section.

Challenges identified related to the E80 Cooper design load and railroad bridges

This survey-based study identifies the following structural engineering research challenges and opportunities related to the use of E80 Cooper load (E360) as live load for the design of railroad bridges in North America:

1. Studying new live load definitions that better represent the railroad load conditions today. The Cooper E80 load came from a steam locomotive loading pattern that today is no longer representative of the actual railroad loading in North America (mostly composed of diesel engines locomotives).
2. In particular, railroad engineers expressed their interest in using new technologies available in the structural engineering profession today. These

new tools would better define live load effects on railroad bridges. RR engineers pointed out the value of this type of research for singular RR bridge cases, such as HSR or long span bridges. They are interested in new design and/or analysis methods that apply actual live loads to complex bridge and/or loading configurations.

3. On the contrary, another group of experienced structural engineers broke down the difficulties related to re-defining the philosophy and ultimately the live load definitions used to design RR bridges. According to them, the Cooper load has been proven to work for many years. They concluded that it would be difficult to propose a new, different live load design approach to the railroad engineers in charge of design and maintenance. It should be pointed out that this suggestion came from both the contracting and the railroad fronts.
4. Finally, a group of railroad engineers with experience in maintenance and replacement of railroad bridges expressed their preferences regarding the measurement of RR live loads. These engineers prioritized the work towards determining bridge performance under live loads, in particular real-time bridge assessment. This group of RR experts emphasized the value of live load responses for RR bridge evaluation.

In conclusion, most railroad bridge structural engineers acknowledge the fact that the current design live load formulas from the MRE recommended practices have passed a century of use. Most of the RR bridge structural engineers interviewed are satisfied with the conservatism of this formula and method. However, there is a significant interest in refining means and methods that (1) measure and identify the effect of live loads on RR bridges and (2) better define current live load values applied to be implemented towards both design and analysis.

3.6 Bridge approaches

Background on bridge approaches in railroad bridges

According to a spectrum of interviewees with significant field experience, the quality of a railroad bridge approaches directly impact a bridge's overall structural performance. This group of engineering experts pointed out the change in stiffness through time between the portion of track immediately outside the bridge (which they call "bridge approaches"), and the track within the two abutments of the bridge. This evolving change in stiffness is caused by a transition from the track bed (softer support) to the railroad bridge infrastructure (stiffer support). Impact loads increase in bridge approaches due to the raise in stiffness differences with time between bridge and approaches. The rise of impact loads caused by bridge approaches damages the structural integrity of both approaches and bridge elements. As a result, railroad bridges extended life and maintenance operations are adversely affected by decay of quality in bridge approaches.

Figure 3.7 helps explain the different load paths that go from the superstructure into the ground before and after the train is on a bridge by showing the elevation of a typical railroad bridge substructure. This bridge substructure is composed of driven piles with concrete caps for both piers and abutments. When the train is outside the bridge, the train loads are transferred to the ground and supported by the ballast, sub ballast, and ultimately by soil layers. In Figure 3.7, this area is represented by the granular materials

up to 6 ft - 6 m deep (indicated by a different pattern). When the train is on the bridge, the train loads are being carried directly from the bridge deck to the pier and abutment caps, and down to the supporting piles, which ultimately pass on the loads to the soil layers underground.

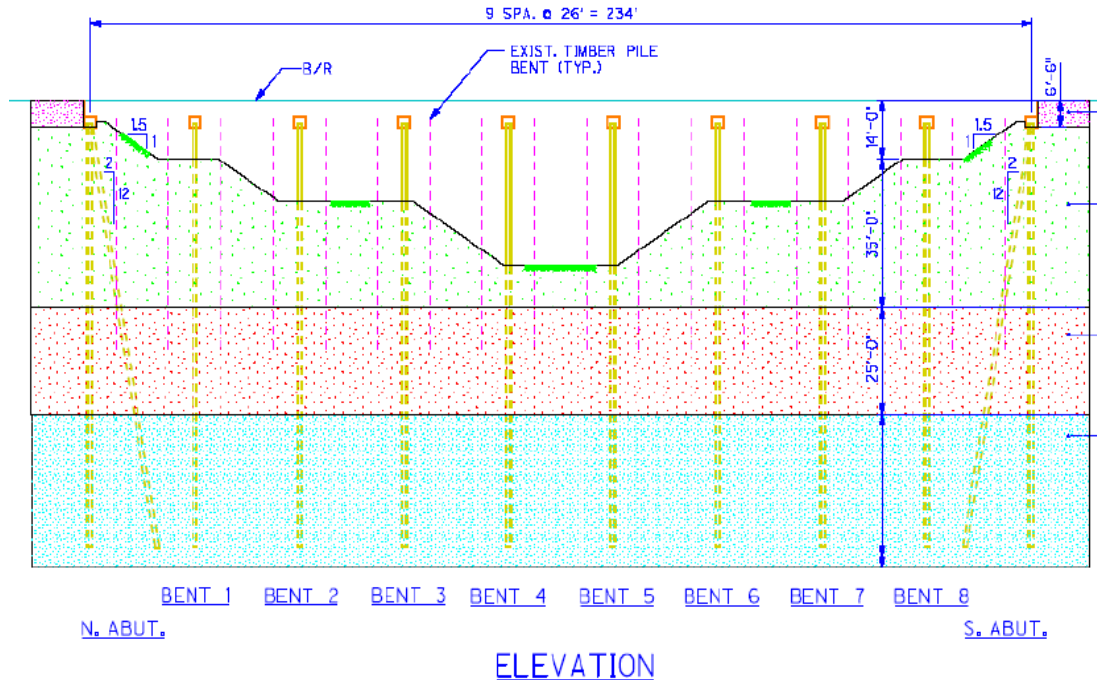


Figure 3.7. Railroad bridge infrastructure elevation (Unsworth and Payne, 2006).

In summary, the substructure of the bridge rigidly supports the track within the bridge region, as opposed to the approaching area, which lacks such a formal substructure to rigidly carry the track above. Due to a difference in track stiffness within and outside the bridge, there will also be a different train and track interaction. The change in stiffness affects the continuity of this interaction. The bridge approaches are the areas in which the transition of different vehicle and bridge interactions takes place.

It is in the bridge approaches area that the train suddenly transitions from an outside to an inside region. To control these changes in stiffness, railroad bridge approaches are designed to provide this transition between the track inside and outside the bridge. A typical railroad bridge approach is shown in Figure 3.8: the bridge superstructure is at the right hand side of the drawing, while the region tagged as backfill is the bridge approaching area.

What do we call a railroad bridge approach?

Railroad bridge approaches are the immediate regions placed on both sides of a railroad bridge, typically within 10-20 ft (3-6 m) from the bridge backwalls. Bridge backwalls serve as a boundary between the railroad bridge and the bridge approach (see Figure 3.7). When needed and feasible, approaches are designed with systems or methods providing a transition between the regions approaching the bridge and the area supported by the actual bridge structure. Traditionally, the simplest version of a bridge approach is composed of backfill materials, which are firmly compacted during the bridge

construction phase to a deeper profundity of the standard railroad track supporting the rail.

It is worth noting that, in most cases, the transitioning bridge approaches are designed and built as a part of the railroad bridge. In particular, bridge design specifications include drawings and contract documents for the bridge approaches. Additionally, bridge contractors build and bill railroads for the bridge approaches. Bridge approaches are part of the bridge bill of materials. The maintenance of the approaches is typically the responsibility of railroad track departments and maintenance of way resources.

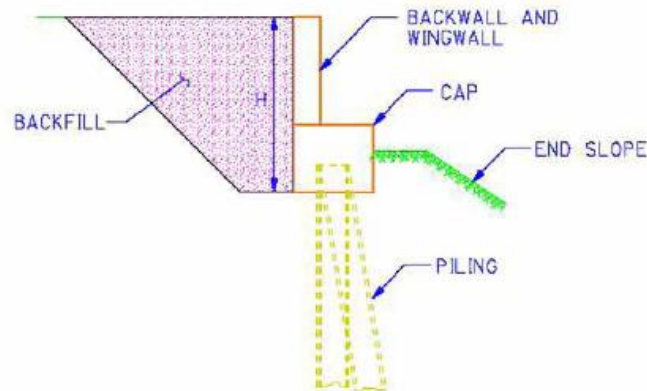


Figure 3.8. Typical railroad bridge approach (Unsworth and Payne, 2006).

In summary, railroad bridge approaches are conceptualized as strict bridge elements during the design, bidding, and building phases of the bridge construction. However, the day after the bridge is put into service and open to train traffic, approaches become a track maintenance item within the railroad.

Past and current discussion related to railroad bridge approaches

During the interviews, some of the bridge maintenance engineers emphasized that deficient railroad bridges approaches cause maintenance problems to railroad bridges. As described in the previous section, the difference in stiffness supporting the track on both sides of the bridge backwalls causes a sudden change in the reactions to the vertical loads from the railroad cars. A larger difference in stiffness will cause a bigger change in the reactions.

The size of this stiffness variation depends on diverse factors related to the characteristics of the specific railroad bridge under study. The group of experts in railroad bridge maintenance interviewed put emphasis on the following bridge properties that affect the difference in stiffness on both sides of the bridge back wall:

1. Open deck structure versus ballast deck: open deck structures have a bigger stiffness change in the superstructure than ballasted decks.
2. Span length, along with other geometrical configurations affecting the rigidity of the bridge structure, affects the transition from the track to the bridge.
3. The section profile of the approaching track outside of the bridge additionally influences the operations of track maintenance and consequently the integrity of the backfill behind the backwalls of the railroad bridge (see Figure 3.8).

The effect of approaches to the railroad bridge performance and maintenance has been addressed by the railroads in the design, construction, and management fronts. The following three examples of railroad bridges approaches design practices were presented during the interviews process and reviewed in literature collected for this study.

In the first place, some of the bridge engineers involved in the maintenance of timber bridges in medium and short lines showed significant interest in developing new studies toward the design of railroad bridge approaches that provide a better transition in stiffness for the track transitioning from the track region to the bridge. Some of the engineers in this group mentioned previous research addressing this problem for timber trestles and other short span bridges. They mentioned work proposing different tie spacing patterns laid out in the bridge approaches region that provides a more gradual stiffness transition for the track transitioning from the approaching region to the bridge.

Secondly, a significant number of the structural bridge engineers in charge of Class I railroads pointed out that traditional design practices commonly address the unknown increase of the IF factor with time by adjusting their computed IF for specific bridges (see section 3.7 “IF in railroad bridges”).

Finally, some of the discussions proposed designing a new transitioning element for the bridge approach. The engineers carrying out these conversations suggested adding approaching slabs to the railroad bridges. In particular, they proposed implementing the bridge approach pavements traditionally used by DOT’s in railroad bridges. Figure 3.9 shows a typical DOT highway bridge with slab approaches in both ends. Figure 3.7 and Figure 3.8 show railroad bridge elevations. DOT bridges, such as the one shown in Figure 3.9, have developed approach standards that successfully provide a transition between the bridge and the approaching road that could be adapted and implemented for railroad bridge approaches.

Regarding the research efforts undertaken by railroads for bridge approaches, several studies identified during the interviewing phase and the literature review are presented in the following paragraphs. They are listed in three groups of publications comprising findings.

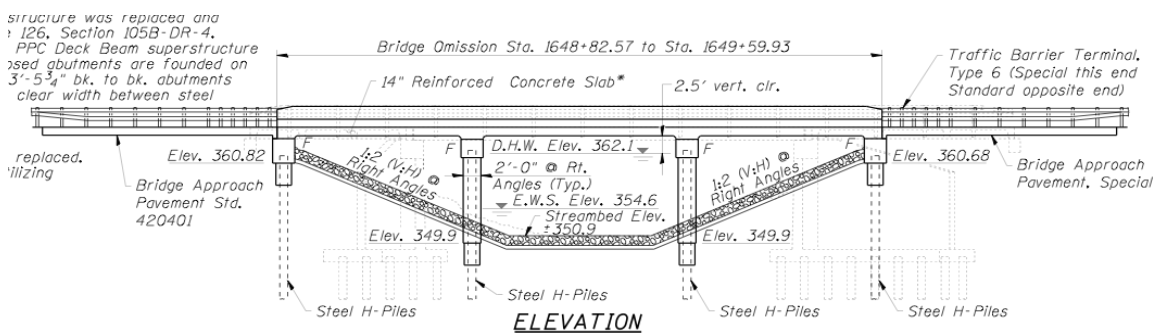


Figure 3.9. Typical DOT highway bridge with slab approaches on both ends.

In the first place, this survey-based study has found that in recent years AAR engineers have generated significant research in railroad bridge approaches. In 2003, *Railway Track and Structures (RT&S)* published research dedicated to railroad bridge approaches (Davis et al., 2003). Their work described part of the research carried out in both the TTCI track as well as U.S. revenue-service lines. Results from this investigation identified correlation between the stiffness changes in bridge approaches and the dynamic

load factors measured in those locations. This study described the causes and the effects of railroad bridge approaches in load factors. Finally, this research explored possible mitigation solutions to the sudden change in stiffness from approaching track to bridge regions and described the trial installation of stone columns in the bridge approaches of the UP railroad company.

Secondly, various track transition designs have been studied by other studies defining problems and remedies to the design and maintenance of railroad bridges approaches. These studies were sponsored by the Federal Transit Administration (Transit Cooperative Research Program; Result Research Digest 79), and collected and published by Read and Li (2006). Li and Davis studied the problems associated with the transition of railroad bridge approaches by defining this as a track transition problem (Li and Davis, 2005). Finally, new research has advanced the work studying railroad bridge approaches and the concerns about the effect of HH load to existing railroad bridge approaches (Li et al., 2010)

Thirdly, research conducted at Texas A & M University (Nicks, 2009) showed that approximately half of the railroad bridges under service are affected by a bump at their ends, costing railroads \$26M (not including costs caused by speed reduction due to bridge approaches decay) (Nicks, 2009). This coincided with previous research in that this bump is in most cases generated by the difference in stiffness between the bridge and the approaching track outside of the bridge. In this study, Nicks modeled the railroad bridge approach and investigated farther effects influencing the magnitude of the bridge approach response under train traffic. Finally, Nicks proposed mitigating solutions that will reduce the negative effects of bridge approach transitions to the railroad traffic.

Current challenges related to railroad bridge approaches

This survey-based study identifies the following structural engineering research challenges and opportunities related to the approaches to railroad bridges in North America:

1. Many of the bridge engineering experts suggested researching new designs (including modeling and testing) for standard railroad bridge approaches. This group of engineering experts suggested studying and developing new approaches that could attenuate the current costs dedicated to maintenance and repair. This proposed research for railroad bridge approaches could cover, but not be limited to, any of the following research areas:
 - a. Study of developing and implementing new materials for railroad bridge approaches. The new bridge approaches could be designed in a similar fashion to that of the concrete approaching slabs used by DOTs to transition from the road to the bridge. The literature research conducted during this survey-based study concluded that the railroad industry has carried out extensive experiments and studies on the concept of a transitioning slab for railroad approaches. In particular, some of the interviewees described past experiments carried out to validate this idea. The railroad bridge experts described a slab with changing width. The perpendicular dimension of the approaching slab would transition linearly from the beginning of the slab (narrower section) toward the beginning of the bridge (wider section).

- b. Study different layouts and spacing for the railroad ties placed in the approaches to the railroad bridge. Different spacing of these ties, as well as their material properties, could be designed in order to explore different ways of obtaining long periods of service life. This research varies from that described in (a) because it involves additional studies on tie materials and track components and the mechanics affecting their connections and performance under traffic loads.
 - c. Research in geotechnical models and new design elements that mitigate the effects of the change in stiffness of approaches with geotechnical techniques as soil reinforcement (Nicks, 2009) or the use of stone columns (Davids et al., 2003; Li and Davids, 2005; Read and Li, 2006; Li et al., 2010).
 - d. Studies related to attenuating the difficulties related to the upgrade of existing railroad bridge approaches that are already functioning under railroad traffic. AREMA members surveyed in this study pointed out that any proposed study, such as those listed in points (a), (b), and (c), would need to address how to install any of the remedial solutions to existing bridge approaches currently open to traffic.
2. A significant group of railroad bridge structural engineering experts suggested developing new research to measure values of IF in railroad bridges under train traffic. This group of engineers proposed to relate the IF measurements to the characteristics of the railroad bridge approaches (see section 3.7) in which they were taken. In particular, they primarily coincided with past studies in railroad approaches about the need of modeling, field testing and laboratory experimentation of railroad approaches (Nicks, 2009). Based on conversations maintained with university researchers, railroad representatives, and structural engineering consultants, there are not many theoretical studies available in which the effects of the transitioning approach are quantified or measured and directly correlated to the IF formula provided by AREMA. According to this survey-based study, there is a need for the development of both testing and modeling of railroad bridge approaches. The modeling and testing of railroad approaches could be correlated with the measurements of the IF under traffic. This research could propose a correlation between different variables defining railroad bridges approaches with IF formulas proposed for specific railroad bridges. The next section in this survey-based study presents a deeper discussion about research proposed related to the impact force measurements and formulas for railroad bridges.
3. Finally, a group of both railroad and consulting structural engineers with experience in the design and construction of railroad bridges in North America suggested researching what has already been done at both TTCI (AAR) and the construction site to attenuate this problem. A critical factor of this research would be to gather, classify, and understand what has been tried and used in different environments and circumstances. This research would differentiate what worked in the past to attenuate the loads from what did not work. This research would ultimately propose a standard application if/when possible to the different railroad bridges types in North America. The group of

experts interviewed pointed out that to develop new standards for every railroad bridge type would require an extended collaboration between research forces and all of the railroad industry players, including owners, designers, manufacturers, and contractors.

3.7 Impact Factor (IF) in railroad bridges

Railroad IF background

Section 3.6 of this report discussed potential research topics associated with current problems in railroad bridge approaches. Part of the research associated with the current problems in railroad bridge approaches identified past investigations related to the effects of impact load in railroad bridges. These numerous studies and reports help show that research of the live load in railroad bridges is often a priority for railroad bridge structural engineers.

In 1970, William Byers published some results of research proposing a probability approach to the determination of impact loads in railroad steel bridges (Byers, 1970). During the course of this survey-based study, some of the consultant and railroad structural engineers referred to Byers' research when asked about IF research. This group of interviewees suggested Byers' work as a good example for studying variables affecting IF values with expected IF values from a probabilistic point of view.

Almost two decades after the publication of the results of this study, the railroad bridge structural engineering community opened new discussions about the need for research about the IF in railroad bridges. In particular, conclusions and results from the 1987 NSF Workshop ranked the impact investigation and its effects as the second most important priority for railroad bridge structural engineers working in a railroad company. Results from this same workshop concluded that when the group ranking research priorities was composed of all kinds of railroad bridge structural engineering professionals, the same category (IF studies) ranked third (Foutch, 1989). The complete ranking of the main research priorities identified during the 1987 NSF Workshop and as collected by Foutch in 1989 is available in Table 1.1 (Byers and Otter, 2006).

A paper published at the RT&S presented the historical evolution of IF studies in concrete bridges (Skaberna, 1988). This paper found that present American and European Codes at the time of the publication provided safe IF parameters. As part of their conclusions, the authors added that more economical approaches could be explored and proposed for the design of RC railroad bridges.

The book *Dynamics of Railway Bridges* written by Ladislav Fryba defines past work and theoretical approaches related to the impact forces experienced by railroad bridges, ranging from testing results and experimental data collection to theoretical conclusions and suggestions (Fryba, 1996). As pointed out by some of the consulting engineers interviewed, the theoretical work presented by Fryba is primarily based on the European experience. Nevertheless, experienced railroad engineer experts in railroad bridges dynamics consulted during this survey-based study recommend this book for an understanding of theoretical approaches to model the dynamics of impact forces in railroad bridges, including vehicle-bridge interactions. Figure 3.10 shows a theoretical model presented in this book as presented in a past publication reflecting track irregularities (Fryba, 1972).

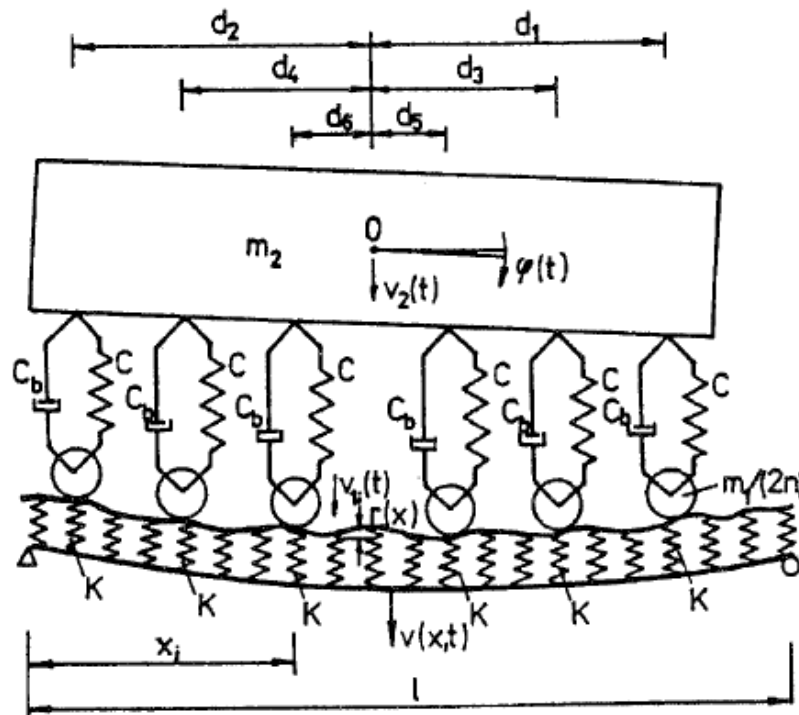


Figure 3.10. Theoretical model of a multi-axle vehicle of the Czech Railways (Fryba, 1972).

Finally, during the course of the interviews, several structural engineers in charge of railroad bridge management and maintenance referred to recent unpublished studies assessing the extension of the life of steel railroad bridges. According to these group of structural engineering experts in railroad bridge management, this work has developed some general guidelines from field data that determines the use of speed restrictions to reduce IF in certain railroad bridges.

Definition of IF by AREMA

AREMA defines the IF affecting the design of railroad bridges in Chapter 2 (Structures) of the MRE (AREMA, 2009). For the purpose of this discussion, the following definition is taken from Chapter 8 of the MRE. Other chapters of the MRE, including Chapters 7 and 15, have different formulas and definitions for the IF value. For further descriptions of the IF refer to the MRE directly (AREMA, 2009).

According to Chapter 8 of the MRE, impact forces applied at the top of the rail shall be added to the axle load specified. For rolling equipment without hammer blow (diesel, electric locomotives, tenders alone, etc.), the impact shall be equal to the following percentages of the live load:

For $L \leq 14$ feet,	$I = 60$
For $14 \text{ feet} \leq L \leq 127$ feet,	$I = 225 / \sqrt{L}$
For $L > 127$ feet,	$I = 20$

(For $L \leq 4$ meters,	$I = 60$
For 4 meters $\leq L \leq 39$ meters,	$I = 125 / \sqrt{L}$
For $L > 39$ meters,	$I = 20$

Where: L = Length in feet (meters) of the span (AREMA, 2009)

As noted in the MRE, these formulas are intended for ballasted-decks and substructure elements as required. The IF may be omitted in the design for massive substructure elements which are not rigidly connected to the superstructure. For steam locomotives with hammer blow, the IF calculated shall be increased by 20%, according to the MRE (AREMA, 2009).

Previous topics of discussion about IF

In the 1960s, the AAR wrote many reports that showed results of the railroad bridge research measuring and validating IF values under specific railroad traffic. The findings and conclusions of this research were extensively validated with in-field monitoring and data collection, as shown in the numerous reports resulting for this extensive research program sponsored and published by the AAR (1961, 1962, 1964, 1965, and 1966).

A few decades later, researchers conducted parallel studies on other continents investigating the nature and value of IF for railroad bridges. In the conclusions of their research, Muller and Dux presented results in which strain measurements from their instrumented bridge test beds often exceeded code values for IF. Their work (which was carried out in Central Queensland, Australia), modeled and measured the dynamic effects of HH loading in prestressed concrete (PC) bridges by characterizing the IF through stresses measurements and comparing them to estimated code values (Muller and Dux, 1988, 1989).

A few years later, as a consequence of the 1987 NSF Workshop (Foutch, 1989), research bridge structural engineers published similar results of IF research at a different railroad in a report entitled “Loading Spectra and Response for a Railway Bridge on a Mixed Freight and High Speed Intermodal Line” (Foutch et al., 1992). In this study, these engineers calculated different IF values for several railroad bridges as part of an extensive research plan that came out of the 1987 NSF Workshop. Following the recommendations collected during this workshop, this research program took some field measurements that studied the IF values capturing the measured behavior of railway bridges subjected to modern freight environment.

In that same year, the AAR published research results from field measurement collecting the responses of test trains operated at different speeds. The conclusions of these studies identified the different impact effects on prestressed concrete bridges. The results of the testing of three bridges assisted in the determination of IF values to help the evaluation of HAL on existing bridges as well as the design of new prestressed concrete bridges (Sharma, 1992). Later, static and dynamic testing of a through-truss bridge was conducted to measure IF values and compare them to calculated values. The results of the testing program that followed the 1987 NSF Workshop showed that the measured stresses were always smaller than the calculated ones. However, the stresses measured in this truss during this research were found to be larger than the theoretically calculated ones (Sharma et al., 1992).

Later in the 1990s, new studies sponsored by the AAR and the NSF monitored the response of three prestressed railroad bridges under train loads. This research program was funded to study the IF of railroad bridges (Gamble and Sharma, 1995). The authors of this research found that the measured live load stresses were low, indicating that these bridges are safe for HAL (Gamble and Sharma, 1995).

Finally, in 2008, a study conducted in Pueblo, Colorado, by the TTCI collected data from different testing settings. These experiments modified the stiffness of the track by softening it. The intent was to reduce the IF imparted to the ballast deck, by means of installing a ballast mat under the ballast throughout the entire length of the bridge. The results of this study are recorded by TTCI (AAR) studies published by Akhar et al. (2008). This work showed the attenuation of the IF under different loadings, including loads as high as 315,000 lbs (143 metric tons)/car (see section 3.8).

Challenges identified involving the IF in railroad bridges

This survey-based study identifies the following structural engineering research challenges and opportunities related to the IF for railroad bridges in North America:

1. According to a structural engineer involved with both the design and maintenance of railroad bridges, a correlation between high speed traffic and IF values could be studied with field equipment on existing railroad bridges. Their attenuation could be tested in a new research set-up bridge test bed. A relatively heavy drop weight could be guided as frictionless as possible on the rail. Then, a spare piece of rail could be hit and different railroad bridge deck responses could be recorded. The resulting measurements and frequencies could be monitored and compared. Certain frequencies generated could be compared to the IF values measured, and these two correlated values could be used for bridge design and maintenance purposes. The same structural engineer added during the course of the interview that a portable truck mounted rig could be installed and applied in less than half an hour of track time for the testing of real RR structures.
2. Venuti and Huebsch studied the dynamic effects of the live load in RC railway bridges. In their studies, they indicated the importance of developing more precise studies and models to better capture and represent the actual dynamic effects of live loads in concrete railroad bridges. According to Venuti and Huebsch, new formulas could be developed for dynamic effects, or at least consideration for further research and modeling should be encouraged. They concluded that further research and development in the IF determination could provide the railroad industry with a more economical and precise impact load determination (Venuti and Huebsch, 1980).
3. In 2000, the IF values measured for different short span lengths were compared to the impacts equations used in AREMA under unpublished materials, according to some of the interviewees of this survey-based study. The comparison of the impact loading calculated with the field data collected in TTCI (AAR) could help assist developing new IF equations based on mechanical models that could further develop the empirical equations being used today by the railroad industry.

3.8 Effects of transitioning from 286,000 lbs (130 metric tons)/car to 315,000 lbs (143 metric tons)/car

Background of the current 286,000 lbs (130 metric tons)/car load in U.S. freight railroads

Since the creation of the TTCI (AAR), their researchers have measured the effects of increasing loads per axle crossing railroad bridges. The *Railway Age Magazine* published some of the results of research conducted by the TTCI (AAR) (Anonymous, 1989) evaluating and comparing the structural integrity of existing railroad bridges under such changes in load. Related studies carried out in the past 15 years evaluated the effects of similar changes in loading to railroad bridges (Byers and Otter, 2006). Finally, Byers and Otter concluded in their studies that these same research topics will be of significant interest for further research in the future (2006).

Definition of the loading per axle in railroads

The common maximum load per axle currently being allowed by a Class I railroad today is 286,000 lbs (130 metric tons)/car. The maximum load assumed by the railroad is used in numerous decisions involving the planning, design, management, and maintenance of railroad bridges. This maximum load is also used to deal with other aspects associated with railroad engineering, including the design of their infrastructure and track components. Nevertheless, due to reasons that will be discussed later in this section, there are some exceptional railroad routes and bridges in North America that are designed to carry as much as 315,000 lbs (143 metric tons)/car (Unsworth, 2003, 2010).

The value of the load per axle used by railroads for railroad engineering design and planning has gradually increased throughout the years alongside the evolution of the railroad equipment and locomotives (Unsworth, 2003). Specific projects typically use individual load per axle values that are dictated by the railroad department overseeing that project. For example, engineering and transportation departments may dictate the maximum load per axle to be used for the design of a railroad project and its different components (bridges, track). Railroad bridges in North America are designed to carry different maximum loads per axle depending on their route, traffic, demand, or other related factors affecting bridge capacity. Some railroad bridges are designed (and/or rated) to carry a maximum load not to exceed 263,000 lbs (130 metric tons)/car, while others are being designed (and/or rated) to carry up to 315,000 lbs (143 metric tons)/car.

For example, a railroad may need to satisfy an upcoming transportation demand in a given specific railroad route. To accommodate a higher load per axle demand, some of the railroad bridges in that railroad route will need to be upgraded to provide enough load carrying capacity. However, railroad bridges cannot be upgraded without a fixed cost. If railroads could foresee the needs of future upgrades in load capacity ahead of time, they could plan their design, construction, and maintenance and save capital investment by anticipating future expenditures during the planning stages. It is generally accepted by the majority of the interviewees of this survey-based study that a better understanding of the effects of higher loads to the structural capacity to existing railroad bridges will improve their design, management, and maintenance, and this understanding should be promoted and encouraged if future research funds become available.

Finally, the increase of loads and their effect in the serviceability and performance of existing bridges is of paramount importance to the railroad bridge engineers. Railroad bridge engineers interviewed agreed that this understanding could assist them in deciding if existing bridges could be upgraded to their next load capacity level. Experts in railroad bridge structural engineering in this survey-based study expressed interest in studies that could identify which elements, connections, or members could be upgraded to attain a higher load per axle category for the entire bridge.

Loading in heavy haul railroads discussion

To allow their networks to carry heavier loads, railroad companies often study the viability of increasing the capacities within their routes. According to the IHHA, the cost associated to the upgrade of their bridges within those routes typically represents a significant percentage of the total, thus becoming a critical element of decision (IHHA, 2009). Those bridges with insufficient capacity will need to be upgraded in order to accommodate the new load per axle. The structural engineering challenges will be directed towards the evaluation and upgrading (if needed) of these existing bridges for the new loads.

According to the IHHA, bridges built with different materials need to be upgraded differently. Independently of the bridge materials, the first step toward determining the repairs and upgrading methodology is generally the load rating of the bridge. As part of the load assessment and upgrade, steel bridges may require fatigue studies, whereas timber bridges may need a complete replacement to secure a solid, reliable new foundation that can support new loading demands. According to railroad bridge structural engineering experts in timber trestles interviewed during this survey-based study, it is common to completely substitute existing timber trestle bridges on specific routes that need to be upgraded. In these cases, the same group of structural engineering experts pointed out, the bridges replacing the timber trestle are often made of new steel H-pile deep foundations that support RC pier and abutment caps. The superstructure of these bridges will be either PC beams or new steel beam elements, depending on the spans lengths of the new bridges.

Studies conducted in recent years researched the correlation between the upgrading of loads in the railroad system with their cost and economic impact (Resor et al., 2001). The main emphasis of this study was short-line and regional railroads. In their conclusion, Resor et al. estimated a cost of \$6.26 billion for the rehabilitation and strengthening of the structures of existing bridges to carry 286,000 lbs (130 metric tons)/car. According to some of the railroad bridge experts interviewed in this research, similar studies could be developed to estimate the cost of upgrading Class I railroads (and those routes requiring upgrades) to the 315,000 lbs (143 metric tons)/car.

The TTCI (AAR) is currently developing extensive research in evaluating the performance of railroad bridges under 315,000 lbs (143 metric tons)/car loading capacity. As recently presented in the 15th Annual Research Review in Pueblo, Colorado, in February 2010, the AAR is evaluating the effects of 315,000 lbs (143 metric tons)/car traffic in existing bridges in their facilities. Constant traffic has been running at their yard in the last few years and both steel and concrete bridges are being monitored and tested (Otter and Joy, 2010).

Figure 3.11 shows two different PC bridges being tested at the HAL FAST track at TTCI (AAR) in Pueblo, Colorado. The two bridges were designed and built following traditional railroad bridge standards. Both bridges are currently being tested under a high traffic condition that reflects future possible HAL exposures of railroad bridges to real life conditions. These experimental settings allow additional areas to be investigated, including, but not limited to, HAL effects on PC bridges, new materials bridge elements, ballast deck bridge IF performance, track and bridge connections performance, and general IF and LF studies.

Figure 3.12 and Figure 3.13 show the DPG being used for the HAL testing at TTCI (AAR) at Pueblo, Colorado. Figure 3.12 shows the original bridge location of the DPG before it was removed for testing. The DPG being tested at the TTCI (AAR) had been carrying trains for almost 100 years, before the bridge shown in Figure 3.12 was removed from open service. Now, this DPG only carries trains at the TTCI (AAR) for HAL testing. Figure 3.13 shows this same DPG in the FAST track. Of the two DPGs shown in Figure 3.13, the DPG that came from the bridge site shown in Figure 3.12 is the span on the left hand side. Some of the recent research work by TTCI (AAR) railroad bridge structural engineers in this DPG was recently described in a *Technology Digest* publication. The conclusions of this research included an assessment of bridge performance under HAL loading before and after DPG repairs. This study measured lateral bridge deflections to monitor the changes in bridge response after bracing repairs were applied to the DPG beam. Their final results showed a decrease in DPG lateral deflection of approximately 30% after the repairs were applied. String potentiometers were attached to the top and bottom flanges in order to measure deflections (Ninness et al., 2011).



**Figure 3.11. PC bridges under HAL testing at Pueblo, Colorado
(Photo courtesy of TTCI (AAR)).**

Challenges identified with HH operations and railroad bridges

This survey-based study identifies the following structural engineering research challenges and opportunities related to the effects of loads per axle in existing railroad bridges in North America:

1. According to some experienced consulting engineers in bridge engineering, the future upgrades of railroad bridges may not become a top research concern in the near future, or at least not one of a pressing nature. This group of

engineering experts reasoned that this has always been an ongoing aspect of railroad bridges and the nature of the railroad industry, as described in the introduction of this section. According to their opinion, demand loads will be periodically upgraded and, as a consequence, existing bridges will need to address that increase by partial maintenance, retrofit, or complete replacement, according to governing financial and economic concerns, when the need arises.

2. On the other hand, TTCI (AAR) has conducted studies in which the increase of HAL on bridges was related to their maintenance (McWilliams and Otter, 1998).
3. Some of the junior bridge engineers surveyed during this survey-based study suggested to research alternative solutions to financially carry heavier loads per axle throughout the system, rather than changing all the bridges in their routes. According to railroad engineers familiar with this concern, one Class I railroad chose to modify the length of their trains to lower the load per axle crossing their bridges. Additional studies in this direction were suggested.
4. The same group of bridge structural engineering experts showed interest in developing financial studies to determine the costs of increasing the load per axle in a railroad route and the viability of that upgrading.



Figure 3.12. Vintage DPG used for HAL testing at FAST track at its original location (Photo Courtesy of TTCI (AAR)).

5. Another group of railroad bridge engineering experts familiar with research being carried out by the AAR favored this research topic as it relates, in their opinion, to recent research being conducted at TTCI (AAR). The research

work that they found of interest was mainly directed to address the IF of heavier loads in existing bridges. During this research, 315,000 lbs (143 metric tons)/car trains had been running constantly over prestressed and steel bridges. The findings and conclusions of this research were recently presented at the 15th Annual Research Review held in Pueblo, Colorado, and published by the AAR. Further studies like this were encouraged during the course of this survey-based study.



**Figure 3.13. DPG installed at Pueblo, Colorado FAST track
(Photo Courtesy of TTCI (AAR)).**

6. Consulting engineers with experience in timber trestle supported this as an important research topic to study and develop. In their opinion, there are many timber bridges in North America that are not able to carry 263,000 lbs (130 metric tons)/car. This group of interviewees pointed out that the performance of timber caps and other timber elements could be a topic of significant interest for research, since in specific cases certain elements of the bridge would be replaced to improve rating categories and upgrade their load capacity.
7. Experts in steel railroad bridge engineering showed significant interest in new research that would study and determine the additional fatigue associated to load upgrading of certain connections in bridge DPGs (Unsworth, 2003).
8. Finally, other experts with experience in railroad bridge design, construction and management declared their preference for studies addressing the performance of long span bridges over large rivers, such as the Mississippi. They would be interested in research identifying the effect of increasing loads per axle in these critical elements of the railroad bridge network. These

experts in structural engineering agreed about the need for specific research conducted to classify upgrading needs for these types of bridges, given the large financial investment required to upgrade and/or replace them, along with studies of the risk associated with not doing so.

RAILROAD BRIDGE MANAGEMENT

4.1 Introduction

On July 15, 2010 the FRA published a final rule on Bridge Safety Standards, establishing new federal safety requirements for railroad bridges. On September 13, 2010 (90 days later) the new rule became effective. The new regulation can be found under reference 49 of the Code of Federal Regulation (CFR), Parts 213 and 237. In general, the contents of this new rule focus on determining both the contents and obligations related to railroad bridge management programs in U.S. In more specific terms, this new regulation enforces new instructions pertaining to inspections, load capacity determinations, repairs, and modifications for railroad bridges (FRA, 2010b).

49 CFR Part 237, Subpart B – Railroad Bridge Safety Assurance, “Adoption of bridge management programs,” points out that “(...) every track owner shall adopt a bridge safety management program to prevent the deterioration of railroad bridges” (p 41303, section 237.31). This same section enforced the adoption of a bridge management program for each Class I railroad by March 14, 2011, and before that date for other different railroads carriers, but not later in any case than September 13, 2012 (FRA, 2010b).

Additionally, “Content of bridge management programs” (section 237.33) defines the requirements for all bridge management programs. According to this section, to comply with the new regulation the contents of the bridge management program should include:

- 1) An accurate and detailed inventory of their railroad bridges
- 2) A record of the safe record capacity of each of the bridges
- 3) A provision to obtain and maintain the design documents of each bridge if available, and to document all repairs, modifications, and inspections of each bridge
- 4) A bridge inspection program (Figure 4.1 shows two examples of typical railroad bridge inspections). The specific requirements of the bridge inspection program required by the new regulation can be found in the reference section under FRA (2010b)

Because railroads in U.S. are different from other transportation systems, their safety practices are regulated differently. In particular, it is traditionally accepted that one of the main differences between the railroads and other transportation systems is that railroads are private enterprises. Consequently, concerns for railroad safety are different than the other modes of transportation. Since safety is typically seen as a potential liability issue, companies want to be protected and hence develop and protect their safety policies as privileged information. Many of the railroad bridge structural engineering experts specified that railroads are an industry of high risk, and as a result, railroads plan the protection of their personnel and their infrastructure as an investment in security and, ultimately, productivity and profit.

Several railroad bridge owners and bridge researchers interviewed during the course of this survey-based study emphasized that railroads are private companies that need to

make money to exist. Railroad owners see railroad bridges as a cost to their annual budget. Related to this, Figure 1.3 shows how almost 10% of the annual capital cost of a Class I railroad company is spent in bridges and structures (Ferryman, 2008). According to related literature found during this research, railroad companies need to prioritize both people and resources within their organization, including the cost of railroad bridges, to make the best use of their money (IHHA, 2009).



Figure 4.1. Bridge inspections for a Class I railroad TPGs from track level (left) and below track level (right).

According to some literature related to bridge management programs, many of the bridge management systems followed today around the world prioritize inspection. These bridge management programs, imposed by either federal or state authorities, were collected in the book *Bridge Management* (Ryall, 2001). Recent studies and research carried out by a Class I railroad further explored the impact of railroad bridge inspections in railroad bridge management decisions. This research wanted to evaluate the ultimate structural capacity of some railroad concrete beams that had been recently replaced by brand new ones in the field. Three of these old railroad ballast deck slabs (over 100 years old) were tested to ultimate capacity for both flexure and shear capacity (Szkolba and Banas, 2006). Some of the test results showed that the load capacities of all three deck slabs were almost equal to four times the E80 Diesel Cooper load. Figure 4.2 shows a picture of the railroad bridge with the old ballast deck slab prior to their testing and replacement.

The results of the testing show that standard visual inspections may underestimate the structural capacity of railroad bridge elements. Moreover, many of the bridge engineering managers interviewed emphasized that railroads want to select for replacement only those bridges that need to be replaced to maintain a safe network. However, many of the bridge engineers interviewed also stressed that visual inspections could be too conservative. They clarified that visual inspections may select bridges that may look unsound despite the fact that their structural load carrying capacity is intact.

As shown in Figure 4.2, the exterior decay of the deck slabs and the maintenance costs associated with maintaining the ballast retaining properties of the curb were the

main motivations for the replacement of the existing deck slabs. Nevertheless, the results of the experiments showed that the structural capacity of the beams exceeded what was needed to carry trains from a structural point of view. If the railroad could know the structural capacity of their bridge elements, more cost-effective decisions could be made in regards to bridge repair and/or replacement prioritization.

Railroads could improve their bridge replacement prioritization policies and methods if they had the means and methods of assessing the structural integrity and performance of their railroad bridges in the field. Railroad companies would be able to safely and cost-effectively maintain their bridge inventories by separating those structures that should be changed from others that have enough capacity, thereby administrating their bridge costs in a more efficient way.

Railroad timber trestles also play an important role in the railroad bridge management in the U.S. Figure 4.3 shows a DPG supported by concrete piers over an interstate road, as part of a timber trestle railroad bridge by Seattle, Washington. Even when the construction of timber trestles is limited to medium and shorter line railroads in North America, there are many existing timber trestles functioning that need specialized inspection and assessment for their proper management. Section 4.5 Management of railroad timber bridges in the U.S. provides further discussion on and insights into this topic.



Figure 4.2. Railroad bridge deck slabs over hundred years old replaced by the CN and tested to estimate their ultimate load capacity.

The understanding of railroad bridge inspection policies and methods can assist in maximizing the knowledge of bridge inventories of railroads. When bridge inventories are properly generated, then detailed information can be passed to the structural

engineering team in charge of bridge assessment, rating, and, ultimately, management. The analysis of the data provided by the bridge inspectors will provide a bridge rating (or bridge capacity). Depending on quality of the data used for the bridge rating, the capacity of each bridge estimated will better reflect the actual bridge capacity. If the bridge capacities are correctly calculated, the railroads can know which bridges structurally need to be replaced first, in conjunction with other factors such as current and predicted future traffic, current resources, investment perspectives, and so forth.



Figure 4.3. Timber trestle bridge over passing a highway with the help of a DPG by Seattle, Washington State (currently not open to traffic).

Railroads rely significantly on the investment and profit margins associated with railroad bridge management in the correct assessment of their bridge capacities. The quality of the bridge inspection records produced help railroads prioritize which bridges are the ones that need to be replaced first, promoting safety operations within the railroad. In this prioritization process, the railroads are seeking a safer railroad network by keeping and maintaining safer bridges, prioritizing bridge repairs and replacements that need to be done first.

The following sections in this survey-based study present the inspection procedures, data collection, and rating policies employed by the railroads in North America. This study includes another section covering the management of railroad timber bridges in North America. The contents discussed for each section include those research topics of areas that can have a potential for PhD studies based in:

- a) The responses or commentaries collected during the current survey-based study
- b) The current literature reviews available
- c) The particular importance given by railroad officials
- d) The significance and potential of current and future studies by railroads and research institutions

4.2 Field inspections for railroad bridges

Background involving railroad bridges inspections

During this survey-based study, a group formed mainly of structural engineers in charge of bridge management showed special interest in means and methods to improve the assessment of the safety and integrity of railroad bridges under open train traffic. These bridge engineering managers showed an interest in developing tools that could assist railroad bridge inspectors and consultants to inspect railroad bridges.

According to some railroad bridge structural engineers interviewed during the course of the survey, railroads prioritize their railroad bridge capital investment by putting safety first while keeping the railroad financially operational. Railroads first replace those railroad bridges that are in most need based on their bridge assessment (combined with factors like their criticality to the entire network). Railroad bridge structural engineers assess their railroad bridges by rating their load capacity. Railroad bridge structural engineers rate railroad bridges by using the structural engineering information of particular bridges included in their bridge inspection records.

Engineers working under railroad bridge management departments emphasize the importance of bridge inspection methods and practices. The group of railroad bridge structural engineers interviewed showed interest in the development and inclusion of new inspection tools that could help railroad bridge inspectors. In their opinion, improving inspection methods and tools could assist in maintaining their network functions under safe conditions and profitable margins. According to bridge railroad structural engineering experts, it is important to invest in and produce accurate inspection records to improve railroad bridge ratings and enable efficient management of the entire railroad bridge network. These bridge management experts supported (a) increasing the qualifications of railroad bridge inspectors, (b) investing in their training, and (c) providing them with the best inspection tools and resources. This same group of engineers added that railroad bridge inspection records should be written and collected for easy access and interpretation by anybody within the railroading community. During this survey, they expressed interest in advancing inspection methods and techniques that can be understood and evaluated. Finally, some of the structural engineers interviewed stressed that this inspection philosophy somehow spearheaded concerns in the railroad bridge structural engineering community that lead toward the elaboration of the 2008 AREMA Bridge Inspection Handbook (AREMA, 2008) and, ultimately, the new FRA 49 CFR Parts 213 and 237 rules (FRA, 2010b).

Engineering bridge departments use bridge inspections to determine the structural capacity of their bridges. The rating structural engineer calculates the capacity of a specific railroad bridge by its structural engineering analysis, assessment and rating. If the bridge rating is found to be insufficient, the railroad bridge structural engineer in charge of bridge management will specify the need for maintenance or full replacement. According to this study, bridge inspections are critical to the management of North American railroad bridges.

Related to the importance of railroad bridge management, the maintenance of railroad bridges need to guarantee that (a) railroads can safely operate and (b) the railroad rightly selects those bridges that need to be replaced first. According to the structural engineering experts of this study, the main two goals of railroad bridge managers are to

(1) know the structural capacity of every bridge and (2) sort the urgency/priority of the replacements and repairs within the network.

In conclusion, this study has found that the majority of the railroad bridge structural engineers pointed to how the reliability of the information about the current state of bridge directly affects the following steps determining bridge capacity and repair/replacement actions (as it is also reflected in the new FRA (2010b) regulation pertaining to railroad bridge management programs). Therefore, the backbone of railroad bridge field assessment, rating, and maintenance are railroad bridge inspections. Figure 4.1, Figure 4.2, and Figure 4.4 are some examples of the inspection of railroad bridges in North America. Figure 4.4 shows the inspection equipment to a large span railroad bridge in the Midwest.

Definition of bridge inspections in the railroad

According to the structural engineers interviewed, and especially according to those who spent most of their career as railroad officers, railroad owners are the ones who dictate the contents and frequency of railroad bridge inspections within their own network. Consequently, specific railroad bridge inspection policies and requirements are different within each railroad. As noted by some of the structural engineering experts interviewed during this survey-based study, the FRA does not approve or disapprove the inspection policies submitted by each railroad. Even when the FRA is aware of the railroad bridge inspection procedures by each of the U.S. railroad companies, the FRA do not take responsibility for them, according to a presentation during the 2010 AREMA National Railway Engineering Conference (Davids, 2010).

During these interviews, some of the structural engineers involved in highways and buildings engineering point out that the building community tends to entrust the safety of the structures to the owner of the actual building. In the opinion of these experts in structural engineering, highway bridge inspections are significantly different because transportation infrastructures are generally own by public agencies. However, railroad bridges and railroad companies are owned by private companies. The inspection policies carried out for railroad bridges in North America are different from other bridge inspection policies, such as those enforced for highway bridges or other transportation systems.

Some literature has identified that after the 2007 collapse of a short line railroad timber trestle bridge in Alabama carrying space shuttle elements, the attention towards railroad bridge inspections dramatically increased (Richards, 2007). According to this study, public authorities and media inquirers have been trying to learn more about the way railroad bridges are inspected today. According to the different opinions of some of the railroad bridge structural engineering experts consulted during this survey-based study, this attention was also caused by the fact that during the same summer the I-35 Minnesota highway bridge collapsed, causing the death of 13 people (ASCE, 2011). After the I-35 Minnesota bridge collapse, some researchers noted that highway bridge inventories and records were widely accessible and displayed, whereas the bridge authorities fall short from that openness to share information with the public (Richards, 2007). According to these sources, some FRA and railroad owners had to explain the differences between highway and railroad bridges after being inquired about the availability of their inspection records. Nevertheless, this same source pointed out that

after these explanations, the general public remained still with the same general feeling that railroads have “way too large” of a role in (a) deciding how deep should railroad inspections be and (b) who should have access to the bridge inspection records of North American railroad companies.

Work by Miller predicted that the responsibility selectively made public by the railroads with the U.S. Government may increase in the near future, as well as the methods and means in which their inspections are being performed (Miller, 2007). Another publication in the same year pointed out that particular attention had been paid to bridges owned by Amtrak, significantly increasing the attention generated in the public media in general toward railroad bridges (Cowan, 2007).

Coincidentally, one year after these remarks, AREMA published the *AREMA Bridge Inspection Handbook* (AREMA, 2008). According to the structural engineering experts interviewed, this book came as a result of an on-going effort to providing general standards for railroad bridge inspectors for railroads of all classes, but with an emphasis for Class II and III railroads. In their opinion, Class II and III railroads needed to carry new work in their inspection procedures and programs to match on-going practices already adopted by the Class I railroads, which were collected and presented in the Bridge Inspection Book.

The *AREMA Bridge Inspection Handbook* describes some of the general inspection procedures that railroads need follow when inspecting railroad bridges in North America. As stated in the *AREMA Bridge Inspection Handbook*, these descriptions are to help railroads in rating bridges when following rating methods and assessment as outlined at the recommended practices collected in the MRE (AREMA, 2009). However, the railroad industry experts interviewed clarified that both the *AREMA Bridge Inspection Handbook* and the MRE cover the “recommended” steps needed during the inspection of railroad bridges in North America. In their own words, they provide general guidance toward railroad bridge inspections. This group of experts clarified that the *AREMA Bridge Inspection Handbook* is directed to railroad employees or staff working for the railroad. They added that the *AREMA Bridge Inspection Handbook* was written to cover two goals: (a) general notions of what is expected from a railroad bridge inspection; and (b) details about the different kinds of inspections to be carried out for specific kinds of bridges.

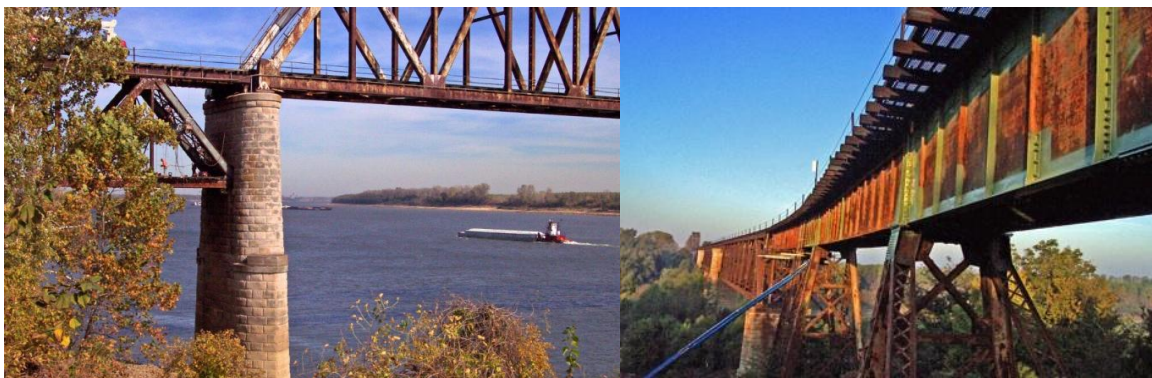


Figure 4.4. Steel bridge inspections and repairs over the Ohio bridge (steel truss by the Illinois side (L) and DPG on the Kentucky side (R)).

North American railroads conduct their own railroad bridge inspections following some general guidelines provided in the federal level as well as those outlined internally as an in-house private regulation; therefore, a certain level of detail remains unknown to outsiders. However, the main general aspects of railroad bridge inspections are today available in both the *AREMA Bridge Inspection Handbook* (AREMA, 2008) and the *MRE* (AREMA, 2009). Current FRA regulation has made effective new requirements for railroad of all Classes regarding bridge management that also affect the way railroad bridges are inspected. The majority of the railroad bridge structural engineers interviewed agreed in the importance of railroad bridge inspections for rating, assessment, and ultimately railroad bridge management. This survey-based study found that developing new research that investigates or improves current means, methods *and* tools for the inspection of railroad bridges would be beneficial for North American railroads. The next section explores current and potential issues or concerns involved to North American railroad bridge inspections.

Current concerns involving bridge inspections

During the course of the interviews, different structural engineers pointed out a range of topics related to the inspection of railroad bridges that, in their opinion, would benefit from additional research. This section shows a selection of the most outstanding research areas identified during this survey-based study.

James S. Ritcher (Deputy Chief Engineer of Bridges and Structures of Amtrak) suggested studying the development of remote inspection devices that can measure and look into remote locations of railroad bridges. Ritcher pointed out that there are many bridges with difficult access to their structural elements, particularly for inspection purposes. According to Ritcher, one traditional structural element traditionally difficult to inspect in the current inventory of railroad steel trusses is the top chord. In these locations, railroad bridge inspectors have a very difficult time in measuring or even performing visual inspections of very high steel trusses. When the weather conditions are adverse, the quality of the inspections decreases significantly in the exposed elements of these structures (Ritcher, private conversation, 2010). The main reason for the decrease of the quality of bridge inspections at these locations, according to Ritcher, is that bridge inspectors have to take measurements and record observations under extreme environmental conditions. Ritcher believes that any device or technique that can measure and/or collect observations of these remote locations would in some degree benefit railroad bridge inspections and the quality of such bridge inspections.

Another topic raised in the course of the interview by some of the railroad bridge structural engineers was that visual inspections could vary from inspector to inspector. Some of the most experienced railroad industry experts went as far as to add that visual inspections also varied from inspection to inspection when performed by the same inspector under different circumstances. Even when visual inspections are on the one hand critical for the assessment and rating of railroad bridges, they are at the same time exposed to the subjectivity associated to the individuals conducting them. Consulted literature coincided with such observations, such as the results collected by research work about highway bridge visual inspections by Moore et al. (2001).

In their research, Sweeney and Unsworth (2008, 2010) found that the current North American bridge inspection's main criterion is to keep the businesses of railroads

working so that railroad traffic can efficiently operate under safe and reliable conditions. They determined that railroads mostly use their bridge inspections to select if their railroad bridges in question need to be (a) repaired, (b) replaced, or (c) kept the same until the next inspection. Sweeney and Unsworth noticed that railroads specific demands govern the inspection policies for each specific bridge. They defined these demands as speed and traffic volumes associated to those bridges; or the presence (or absence) of alternative routes, i.e. the criticality of one a specific bridge to the entire network. Additionally, Sweeney and Unsworth identified a bridge's past history as well as its future expected usages as additional parameters taken into account for determining the specific requirements associated to their inspections. Sweeney and Unsworth concluded that railroads determine the type and breath of the inspections as well as the frequency based on these specific variables associated to each particular railroad bridge. Two bridges with the same structure, the same age, and the same traffic, may receive two completely inspections with two different frequencies of inspection. In these two railroaders' own words, there are not two same bridges in the entire railroad network (Sweeney and Unsworth, 2008, 2010).

As described earlier in this section, railroad bridge inspections are critical to railroad bridge management in North America. The *AREMA Bridge Inspection Handbook* (AREMA, 2008) states that railroad bridge inspections directly affect the actual operations for the entire network. As described in the *AREMA Bridge Inspection Handbook*, if a particular bridge inspection finds unsafe conditions for one particular bridge, railroad traffic could be interrupted. If the bridge inspector determined that the findings from their inspection compromise the safety of trains running over it, they could immediately request a slow order for that particular bridge, or even completely divert/stop the traffic expected for that particular bridge. Finally, the result of this survey-based study has concluded that according to the new federal regulation regarding the safety of railroad bridges (FRA, 2010b), the authorities of the bridge inspector, bridge supervisor, and bridge engineers have been significantly raised with the new railroad bridge management program established by FRA (Davids, 2010), if compared to past attributes and responsibilities for these same titles associated with the management of railroad bridges in the U.S.

A significant portion of the surveyed population of railroad industry experts pointed out that up until recently, North American Class I railroad have managed their bridges with Bridge Management Systems (BMS), which in most cases are computerized today. However, Class I and Class II railroads have not typically implemented BMS to manage their bridge population, mostly because their size and number of bridges could be maintained with less sophisticated or elaborated in-house procedures. However, as this group of railroad bridge structural engineering experts pointed out, the new FRA 49 CFR Parts 213 and 237 rules (FRA, 2010b) enforces the adoption of bridge management programs to all railroads under the parameters presented in the previous section. The implementation of bridge management programs to Class II and III railroads will be a trending issue for these railroads, as well as an opportunity to carry out further research and investigations of means to effectively implement the new requirements regarding inspection of railroad bridges to all classes of railroads (Class I, II, and III).

According to Kube (2007) there are many other aspects of the current bridge inspection procedures in the short and medium railroads that could be investigated. Kube

pointed out that short and regional railroads are responsible for about 17,000 bridges in North America, slightly short of 20% from the total railroad bridge inventory. Kube conducted some research that wanted to assess railroad bridge inspection practices in these railroads. In Kube’s study, several deficiencies were identified between a study of a group of bridge inspection practices conducted between January of 2004 and March of 2007. Some of the results of Kube’s work are included in Table 4.1 and Table 4.2. In the same study, Kube listed recommendations coming from the FRA to be implemented to improve/standardize the current railroad bridge inspection policies in the U.S. (Kube, 2007).

A significant section of the railroad industry experts emphasized another topic related to inspections of the approaches of railroad bridges. In a typical case story of a bridge repair approach, inspections to bridge approaches are conducted when the train traffic going over it notices an abnormal response on the ride. When the train crew notices a different performance while crossing a specific bridge, they report to the structures and bridges department, which inspects the bridge (once the track crew confirms that the abnormal bridge response was not caused by a track problem). Section 4.3 below provides further comments on current data collection practices regarding railroad bridge inspections. That section unveils a new “inspection” methodology that collects bridge performance from instrumentation deployed in locomotive trains.

Table 4.1. Inspection procedures study summary for short and medium railroads (Kube, 2007).

18 of 43 railroads did not produce critical documentation related to the safety of their bridges
Only 16 of the 43 railroads inspected their bridges annually
26 of the railroads subcontracted their inspections
7 did not inspect their bridges at all
4 conducted their inspections in-house
4 did not say who did their inspections
1 had an informal inspection arrangement
1 did not have any bridges

When the railroad is aware of abnormal bridge performance, bridge inspectors and structural engineers closely look the bridge in question. Based on the inspection, and if the bridge department deems necessary after the necessary calculations and analysis performed by bridge structural engineers, corrective measurements are applied to upgrade the bridge. Alternatively, the bridge department of the railroad may propose a partial or complete replacement, whereupon new design and construction contracts would be ordered. The inspection of railroad bridges is the first step in the bridge management

process and plays a key role in railroad bridge maintenance and construction. According to the survey-based study conducted and in the opinions of the majority of railroad bridge structural engineers surveyed, improving bridge inspection will enhance the bridge management of railroads in North America.

As a result, this survey-based study has identified a significant number of challenges involving the inspection of railroad bridges in North America, which are listed in the next section.

Table 4.2. FRA inspection recommendations for railroad bridge inspections (Kube, 2007).

Each railroad shall maintain an accurate inventory of their bridges. If not available by the railroad, a good engineering firm should be hired that can generate this information and make it available
Bridges should be inspected at least annually
Every bridge inspection needs to be entered into a detailed record available to the engineer responsible for the bridge integrity
The bridge owner should designate a qualified bridge inspector to authorize movement after repairs
Communication lines must remain open. Bridge inspectors should be able to contact their bridge engineers directly at any time and in any way possible

Challenges identified related to bridge inspections

This survey-based study identifies the following structural engineering research challenges and opportunities related to railroad bridge inspections in North America:

1. A significant percentage of the structural engineers with consulting experience interviewed pointed out that this topic is particularly sensitive due to the legal implications associated with regulating safety-related activities within private enterprises. From their point of view, inspections of railroad bridges involve many liability aspects affecting railroad bridges’ owners, so research in this area may be limited to small amount of public information available. As a result, this group of engineers believes that not having access to the current inspection data, or guarantees to access it, may limit the amount and quality of research in this area.
2. Another group of railroad bridge engineers pointed out that the inspection practices of railroad bridges could be a good research topic, particularly because this is an area that has not been made public yet. Since the inspection procedures are privately dictated by each individual railroad, they differ (in larger or smaller degree) between the different railroads. Studies and comparisons between the effectiveness of the different inspection programs could enhance inspection practices in the North American railroads.
3. A group composed of structural engineers in charge of bridges and structures for Class I railroads in North America recommended research that explains

and compares the transition from the FRA's general procedures for bridge inspections to the in-house inspection policies of individual railroads. According to this group of railroad bridge experts, the individual railroads follow their own private inspection policy from general guidance and recommendations. According to a representative of a Class I railroad in charge of railroad bridges and structures, the specific levels of inspection followed by individual railroads are developed after the general FRA bridge inspection policies. In this context, this group of engineers suggested developing research in the specific inspection program level of a particular railroad company that transitions from a general visual inspection to a more specific inspection. Research that characterizes signs collected during a visual inspection indicating that a detailed inspection is required for different types of railroad bridges.

4. A group of railroad bridge experts stated that the most valuable inspection is the one measuring what you have in the field. Railroad bridge structural engineers and managers are especially interested in bridge inspections capturing and quantifying bridge responses under railroad traffic. These bridge experts showed a significant interest in the developing and improving North American railroad bridge inspection methods to produce inspection records that quantify railroad bridge performance.
5. According to a group of interviewees composed of private consultant engineers in charge of bridge inspections and experienced bridge inspectors, there is a need to develop technologies and applications that could determine or quantify the capacity of timber trestles. This same group of railroad bridge inspection experts expressed interest in finding inspection tools that can quantify or assess the reliability of the foundations of railroad bridge timber trestles.
6. A group composed of experts working for railroad companies expressed their interest to include bridge performances under live load as part of the bridge inspection records. This group of engineers explained that the performance of railroad bridges under railroad traffic controls many of the design parameters, especially due to the high loading levels under railroad locomotives. They clarified that the ratios of live loads over dead loads in railroad bridges are higher than in highway bridges. This group of structural engineering experts added that live loads impose higher performance demands in railroad bridges as compared to highway bridges or other lifelines. As a result, they proposed studying and developing inspection methods that assess railroad bridge performance under trains and also include them as part of their railroad bridge inspection record.
7. As presented by Sweeny and Unsworth (2008) and Lozano and Kavars (2009), there are many cases in which railroad bridges are not accessible to inspectors except by rail. Some of the railroad bridge engineering experts surveyed in this study pointed out that this limited access is particular within railroads, and not common to other lifeline industries. As these researchers pointed out, railroad bridge inspectors could observe and inspect the bridge elements from the bridge once they have accessed it by rail. However, they

could not access the bridge when a train is crossing it (see Figure 4.5). This group concluded that many North American railroad bridges cannot be inspected under traffic, so their performance under trains cannot be observed or inspected. As a result, they suggested investigating and developing studies or research that could provide methods to can measure the response of railroad bridges under railroad traffic so that they can be incorporated in the railroad bridge inspection documents.

8. Finally, a group of railroad bridge structural engineering experts in railroad bridge management pointed out the need for research that explores methods and means that assess and measure dynamic responses of railroad bridges under railroad traffic. These bridge management experts expressed their specific concerns about the variability of conclusions about the structural integrity that could be made by different inspectors observing the same bridge under the same loading conditions. They concluded that even when a railroad bridge is accessible for visual inspection under traffic, visual inspections vary from inspector to inspector and from inspection to inspection, especially when bridge inspectors are trying to assess the dynamic response of railroad bridges under trains. This group of bridge engineers pointed out that the dynamic performance of bridges would be critical for assessing bridge structural conditions and, in their opinion, should be included in their inspection records if at all possible. These bridge engineers agreed that it is expected that different visual inspections will change more significantly when trying to measure the dynamic response of railroad bridges under traffic than when measuring different properties in the static range. They concluded that today there is a need to provide better tools and methods to inspect the dynamic response of railroad bridges. They added that the collection of dynamic data from railroad bridge responses could significantly benefit their inspection and rating systems as well as, ultimately, bridge management in the U.S. Given the importance of data collection indicated by a significant portion of the group of experts in railroad bridges and structural engineering, this potential research topic is discussed in the next section.

4.3 Bridge instrumentation and data collection

Background on railroad bridge data collection

As noted previously, a significant portion of the railroad bridge inspections are performed without train loads, since many of the railroad bridges within the railroad network are not otherwise accessible. In these cases, railroads perform their inspections by using high-rail cars. High-rail cars are vehicles equipped to ride both on highway and rail environments by switching their trucking equipment. High-rail cars allow access to bridges. Once bridge inspectors reach bridges via high-rail cards, railroads make use of small cranes to bring bridge inspectors under the bridge deck and other areas that need to be inspected. Figure 4.5 shows a railroad bridge inspections by high-rail cars by Class I railroads in North America (Sweeney and Unsworth, 2008, 2010).



**Figure 4.5. Railroad bridge inspection conducted from the railroad track
(Sweeney and Unsworth, 2008).**

Lozano and Kavars (2009) pointed out in some parts of their railroad bridge monitoring research that railroad bridge inspectors today would be interested in measuring railroad bridge responses under dynamic loading. However, in their opinion, railroad bridge inspectors often find difficulties measuring and/or quantifying dynamic responses of railroad bridges under train traffic. Furthermore, as described previously, most maintenance inspection records carried by railroads do not include quantifiable data capturing the dynamic performance of railroad bridges under traffic. According to railroad bridge structural engineering managers interviewed in this research, bridge

response measurements can assist managers in making decisions regarding a bridge assessment that would be based in actual data collected from their bridges. A significant group of structural engineering experts interviewed during this survey agreed with the remarks presented in the 2009 National AREMA Conference by Lozano and Kavars. They would like to develop and research inexpensive ways to measure specific data associated with the bridge performance under railroad traffic.

Research on data collection of bridge response under train traffic has already been conducted in the past. Moreu and Nagayama (2007) tested the use of wireless sensors to measure dynamic bridge vibrations under train traffic in the Midwestern U.S. On October 12, 2005 Moreu and Nagayama monitored two different bridges under four different trains by placing one wireless sensor on different locations willing to record differences in vibrations for different bridge locations and bridge elements. Figure 4.6 shows the wireless dynamic response collection of a timber trestle railroad bridge under regular traffic, by the use of sensors attached to the bridge superstructure. Figure 4.7 shows the installation of the sensors at the bridge (Moreu and Nagayama, 2007). The objective, results, conclusions, and other details related to this bridge monitoring can be found in the reference list at the end of this report.

Research by Sweeney and Unsworth (2008, 2010) compiled details about the different type of railroad bridge inspections in North American railroads. These documents describe the different levels of inspections traditionally observed by Class I railroads in North American with examples detailing frequencies and practices observed by railroad bridge inspectors today. According to the publications from Byers and Otter (Byers and Otter, 2006) the general railroad bridge community has currently a significant interest toward identifying actual levels of railroad bridge response under different loading levels.

Currently, railroads collect the response of the train as it goes on the track to monitor changes in track response (and bridge response, if applicable). According to some of the structural engineers involved with research and development efforts by AAR, North American railroads are developing and researching the use of new electronic devices implemented in locomotives that could electronically record the response of a train as it runs on the track. These devices have a GPS function that records the location of the signals being recorded. In this way, structural bridge experts pointed out, if the sensor in the car collects an abnormal response, the railroad could identify the exact location of that abnormal response within their network. Once the location is identified, the railroad could send track inspector crews to investigate the cause of this abnormal response. They concluded that if the mileage location coincided with a railroad bridge, then bridge inspectors would be sent to inspect the bridge.

The method described above could be used to relate changes in electronic responses measured on the train to changes in the railroad bridge performance over time. Consulting engineers interviewed in this survey-based study pointed out that contrary to the experiences monitoring building responses, railroads could transport their sensors from bridge to bridge without installation costs, since railroads already own the trains running throughout their networks.

Other railroad bridge structural engineers expressed their concern about using of sensors installed in rail cars to monitor railroad bridge responses. These bridge experts thought that the measurements collected by the trains would be unable to record bridge

responses since they would be attached to the train locomotive, rather than to the bridge. As they pointed out, these sensors would measure “car responses” as opposed to “bridge responses.” They added that these measurements could not directly capture or address the train-bridge interaction aspects of the vibration, such as the wheel-rail interactions, different track components and maintenance levels, different types of ballast (or even its entire absence), because these events would be the cause of abnormal train performances. However, in their opinion, sensors mounted in the rail cars could not detect the nature of the abnormal performance by reading the changes in the car performance (above track). They expressed concern that railroads would not have the information to distinguish the cause of changes in measurements from these readings and that these recordings would not indicate if changes in car performance were caused by track or vehicle-track interaction or by an abnormal bridge performance. Additionally, inspections are limited to the very occasions in which the vehicle is on the rail.

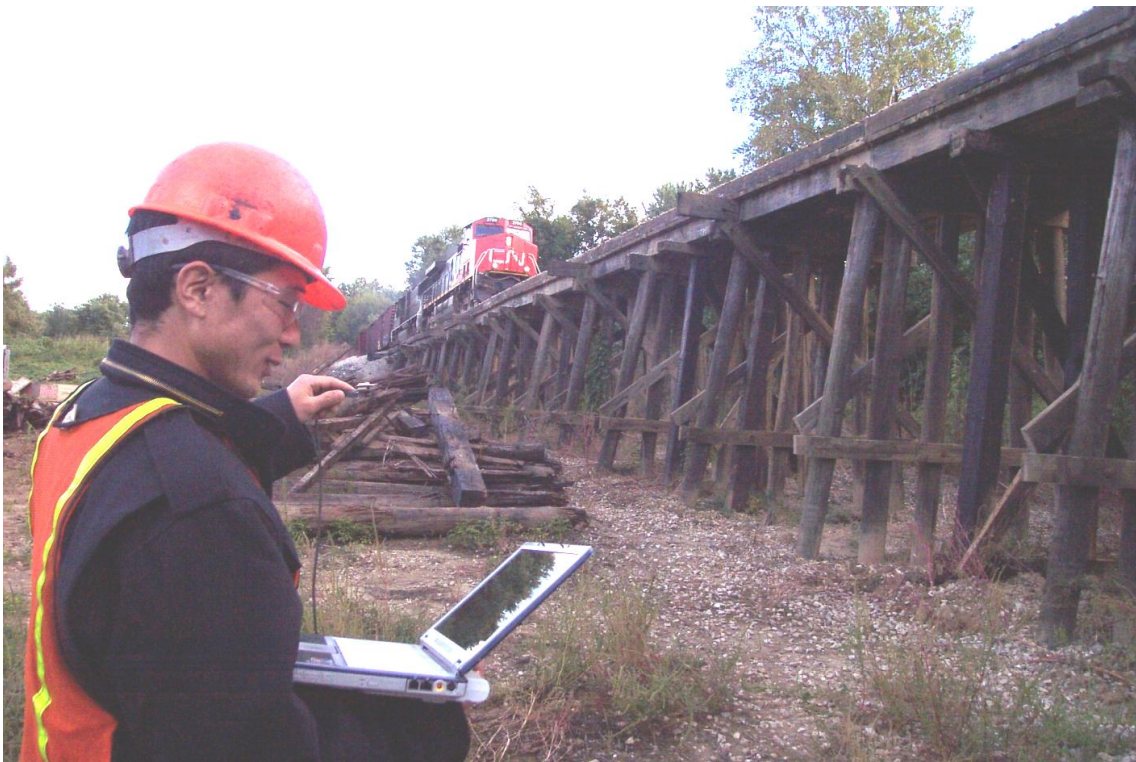


Figure 4.6. First documented wireless data collection for a timber trestle railroad bridge in Kentucky, U.S. (Moreu and Nagayama, 2007).

Nevertheless, based on the opinions collected during the course of this survey-based study, AAR bridge engineers in general find SHM by using sensors mounted on rail cars interesting and promising for research, testing, development, and implementation within the railroad industry.

What do we call “data collection” in the context of railroad bridges?

Data collection practices are not new within the railroad bridge community. According to Class I railroad structural engineers interviewed in this survey-based study, railroads already instrument several railroad bridges today under ongoing railroad traffic. This

section explains: firstly, why railroad bridge owners decide to collect data from their bridges; secondly, two examples of data collection cases are described; thirdly, the concept of data collected wirelessly is introduced; and, finally, individual recollections from railroad bridge owners and managers regarding data collection for railroad bridges are added.

The majority of the monitoring projects involved with data collection from railroad bridges intend to collect data that can be used to address specific concerns associated to individual bridges. According to both railroad bridge structural engineers interviewed and some of the related literature reviewed, railroad managers currently select which bridges they would like to monitor in a one-on-one basis. These same sources indicated that the data collection campaigns are typically governed by the specific needs associated to the particular bridge being measured and the specific parameters that the railroad bridge managers want to measure from their specific bridge managerial goals and objectives.

The following discussion outlines two recent cases in which the railroads have implemented instrumentation programs in order to collect data about the performance of railroad bridges due to specific concerns associated to these bridges.

The first example is related to the monitoring of railroad bridges generated by the concern of railroads to adjacent construction activities, and their effect to the existing railroad bridge. Danielle Kleinshans presented a paper at the 2009 AREMA Conference regarding one specific monitoring project for a railroad bridge. Kleinshans' paper described the monitoring system of the Huey P. Long Bridge widening project in New Orleans, LA (Kleinshans, 2009). Kleinshans described this instrumentation project with further detail in the *Roads and Bridges Magazine* (2008). In these articles, Kleinshans provided a general description of the characteristics of the bridge being monitored, the Huey P. Long Bridge. With three main spans 530, 790, and 530 ft (162, 220, and 162 m) long respectively, the Huey P. Long Bridge total length exceeds 23,000 ft (7 KM), making it the longest railroad bridge in the U.S. In her articles, Kleinshans described the main goal of the bridge instrumentation project to measure bridge responses that would help assessing the performance of the existing infrastructure during the widening of the deck. Kleinshans provided details about the instruments used for the data collection and details about their installation and purpose. The instrumentation work consisted in deploying strain gages as well as temperature collectors, which were connected to the different elements of the bridge trusses. The aim of the installation of these instruments was to obtain whichever data was needed to ensuring both owners and authorities in charge of the bridge that the structure performance was "good" during and after the bridge construction, since traffic could not be interrupted during the widening of the bridge.

Some of the structural engineers interviewed during the course of this survey-based study referred to another instrumentation example related to railroad bridges. They pointed out the importance of monitoring fatigue performance of today's railroad steel bridges. Traditionally, the railroad bridge structural engineering community has developed growing concerns related to the fatigue performance of steel railroad bridges. This is due primarily due to the nature of railroad loading along with the increasing age of current steel railroad bridges in North America. Railroads have explored different and various ways for monitoring and measuring signs of effects of fatigue within their steel railroad bridges inventory. Railroads today employ sensors to monitor the response and

performance of steel railroad bridges considered to be at risk of fatigue degradation. Railroads are using sensing techniques that are currently being used by highways DOTs (Cavaco, 2007). In April 2007, Judge presented and discussed the experimentation of innovative systems recording the evolution of cracks in DPGs in RT&S (2007). Judge's article specifically covered the work of TTCI (AAR) in crack monitoring systems for DPG under HH loading. Finally, Judge's article provided specific steps and strategies toward the measuring and detection of crack growth and propagation, in conjunction to concrete lessons learned about the data instrumentation techniques as part of the final conclusions.

These examples provided show current cases of railroad bridge instrumentation that help understand cases in which railroads today decide to collect specific data from their bridges to ensure their safety. The monitoring of bridges has been ongoing for several decades, in the majority of the cases with wired instrumentation, like the examples described above. In both cases, monitoring has been installed to control specific events like construction activities, the development of predicted events like cracking, and/or the monitoring of abnormal response under normal loading.

Like railroad bridges, the installation of long-term wireless SHM techniques and approaches has been developed to continuously monitor highway bridges (Hoult et al., 2010). These efforts are parallel to current interests within railroads to assess the structural capacity of their bridges. As some of the interviewees pointed out, the use of wireless networks could assist railroads by monitoring railroad bridges structural capacity. Wireless sensors networks could provide inexpensive, practical, and movable sensing strategies that could assist railroad bridge departments in making better decisions about their bridge management.

Related to the practicality of implementing SHM methods for railroad bridge management applications, chief engineers in charge of Class I railroads in North America further clarified that one railroad would not want to spend more money and time in monitoring a bridge than what it would actually cost to replace it. This same group of bridge structural engineering experts explained that current monitoring projects are helping railroads determining actual load distributions on specific bridges. In particular, these strategies allow railroads to prioritize bridge replacements. Based on readings of stress levels from data collected under train traffic, railroad bridge engineers prioritize the replacement of specific bridge elements. The *Journal of Bridge Engineering* published a monitoring work measuring the performance of a railroad truss bridge and directing repair work based on those measurements (DelGREGO et al., 2008).

This section has explained how railroad bridge structural engineering managers choose to instrument railroad bridges and collect data based on the particular needs associated to individual bridges on a one-on-one basis. Secondly, this section has described two specific examples in which railroads have chosen to collect data from individual bridges based on their individual concerns related to those specific cases. Thirdly, the current interest from railroad bridge managers toward inexpensive, portable and practical wireless sensors that can collect data from railroad bridges was presented. Finally, the specific opinions from current chief engineers of bridges and structures were collected in regard to railroad bridge data collection systems.

The next section of this survey-based study will explore in further detail research opportunities collected from the interviewees as well as the potential of applications of SHM techniques and strategies toward railroad bridge management.



Figure 4.7. Wireless sensors installation in a timber trestle railroad bridge.

Current discussions on data collection and bridge monitoring – SHM and railroad bridges

In September 2009, Lozano and Kavars presented a paper at the AREMA Annual Conference, stating how recent DOT studies had shown that accelerometers installed in bridges can successfully indicate structural degradation by measuring frequency shifts of responses. This survey-based study has also previously identified that structural engineering community that railroad bridges cannot be easily inspected under live loading, since due to the lack of access to the railroad bridge, railroad inspection crews have to access the bridges from the rail and therefore inspect bridge components without train traffic (Lozano and Kavars, 2009) (Figure 4.5).

According to Lozano and Kavars (2009), railroads can address this problem by attaching accelerometers to the bridge, which could record accelerations under trains and measure bridge responses for several days for both superstructure and substructure elements (piers). This data could be used as a permanent bridge inspection record for decision-making and managerial purposes by railroads (Lozano and Kavars, 2009). The

AREMA Bridge Inspection Handbook suggested using data collected from railroad bridge responses to improve railroad bridge inspections. AREMA believes that using performance measurements, when available, could improve bridge inspections, as compared to bridge inspections exclusively based on visual observations (AREMA, 2008).

According to the sources consulted and the opinions collected during the survey, North American railroad engineers believe that the collection of railroad bridge responses under train traffic could improve the quality and depth of railroad bridge inspections.

It is generally accepted within the SHM field that there are current difficulties in collecting data and actually using it for managerial purposes by bridge owners. Railroad bridge owners interviewed in this survey-based study believe that there could be a big gap between the collection of data and its final interpretation by railroad bridge structural engineers for decision-making. This study identifies today's goal as transforming reliable data to information that can help owners to make intelligent decisions about the management of their infrastructure.

In the last 15 years, civil engineering has developed research and studies of the dynamic properties of structures that can assist structural engineers assessing their structural performance (Doebeling et.al, 1996). Long-span bridges are being extensively monitored today, as presented in international conferences on bridge maintenance, such as the 2008 International Association for Bridge Maintenance and Safety (IABMAS), entitled "Bridge Maintenance, Safety, Management, Health Monitoring and Informatics" (Koh and Frangopol, 2008).

However, some of the railroad bridge structural engineers identified two different areas in which SHM could be improved if intended to be used to assist railroad bridge owners.

A group of interviewees proposed fostering more developments in SHM for shorter-span bridges would be beneficial. This group of bridge structural engineering experts believed that shorter-span bridges could better capture the correlation between changes in the global structural performance in the bridge and the presence of local defects in some of the bridge elements. Some researchers conclude that studying using SHM methods in short span bridges could significantly benefit owners and infrastructure managers (Brownjohn, 2007; Farrar and Worden, 2007).

Another group of structural engineering experts interviewed believed that identifying the number of sensors to be used, and their optimal placement within a structure, are still challenges that require further research and study, as related literature reviews recently pointed out (Dove et.al, 2006).

A significant portion of the publications consulted during this survey-based study agrees that the application of wireless sensors for bridge monitoring needs further development. With further progress in practical applications toward bridge cases, managers and bridge owners can benefit from the progress obtained up to this point by other SHM researchers (Ko and Ni, 2005; Karuomi et al., 2005). In particular, early studies by Japanese engineers showed in the 1990s the potential of using vibration measurements for structural capacity assessment and were researched and collected over a decade ago (Abe, 1998). More recently, researchers in the Civil and Environmental Engineering (CEE) department at UIUC agreed that even if the history of wireless

sensors was not new in engineering in general, their applicability toward civil engineering infrastructures was still at its early stages (Ruiz-Sandoval et al., 2006). As a consequence, according to this study, the development of applications that record and interpret acceleration records obtained by wireless sensors would also benefit researchers trying to improve the use of sensors for civil engineering applications, in particular those railroad bridge structural engineers interested in wireless data collection from railroad bridges.

As identified in studies by Byers and Otter (2006), there is a significant, growing interest from the railroad engineering community to collect data from bridges in the field and to make this data accessible to the railroad bridge structural engineers in charge of bridge management. All railroad bridge structural engineers consulted in this survey were interested in data collection systems providing bridge performance data. They expressed their interest in methods and strategies that are easy, fast and cheap to install, operate, and interpret. As explained in section 2.4.4, the profile of all people interviewed covered both retired and junior engineers, consultant and contractors, railroad and government structural engineers, so interest comes from all sections and ages within the railroad bridge structural engineering community.

This research has identified past discussions involving implementation of sensors to prevent railroad bridge catastrophes. Those studies found that the installation of sensors to manage safety of railroad bridges was too expensive and would not be justified, due to the large initial investment that would need to be made. For example, in 1981, the FRA estimated the cost for detection devices in the U.S. railroad bridge network at \$850 million to install and \$85 million a year to maintain. The decision of the agency was that the concept was appeal and interesting for research and study; however, in the words of an Amtrak spokesperson “we’ll have to see if it could be effective, reliable and truly useful” (Applebome, 1993). The FRA study was generated as a result of a bridge-related derailment over a damaged bridge in 1979 in Devils Slide, Utah. Subsequent train derailments – like the one in Secaucus, New Jersey, in 1996, preceded by the 1993 Alabama derailment that killed 47 people and injured 103 – stirred the debate about sensor systems installation. According to other research related to railroad bridge monitoring, the cost of installing sensors in bridges ranged from a few thousand dollars per bridge to as much as \$40,000. The total estimate for installing sensors along the entire railroad bridge network reached billions of dollars, with an estimated cost of \$60 million a year for operation and maintenance (Perez-Pena, 1996). Additional information and research investigating the cost-effectiveness of railroad bridges monitoring systems can be found in the study “Overview of Railroad Bridges and Assessment Methods to Monitor Railroad Bridge Integrity” (ENSCO, 1994).

It was noted during the course of this research that the interest from the railroad bridge structural engineering population adds on to past efforts to incorporate SHM into bridges that aim to generate intelligent infrastructures (Aktan et al., 1999).

In parallel with conversations maintained with other experts in SHM tools and techniques available today toward civil engineering applications, this study found that there are many areas in which the development of current research could be used for making this a practical tool for practicing railroad bridge structural engineers. Specific applications that merit further investigation, as well as current challenges in need of further development, have been identified for the case of railroad bridges by the experts

in this field during the course of the survey part of this study and listed in the following section.

Challenges identified related to data collection, bridge instrumentation and SHM

This survey-based study identifies the following structural engineering research challenges and opportunities related to the data collection from railroad bridges in North America, their instrumentation, and their SHM:

1. According to the large majority of the railroad bridge structural engineers interviewed in this study, measuring deflections under traffic would be of great assistance for railroad managers in charge of determining when railroad bridges need to be replaced. According to this study, railroad managers would be very interested in deflection measurement systems that could be quickly and easily installed in railroad bridges by bridge inspectors that could collect the bridge deflections under trains in real-time. Railroads further clarified that they would be interested in measuring movements in the three directions (vertical, longitudinal, and transverse deflections). Recent studies from Chinese researchers identified simplified methods relating dynamic measurements of inclinometers with deflections (Hou et al., 2005). More recently, Korean researchers developed new algorithms that estimate displacements from acceleration measurements (Lee et al., 2009). According to this study, railroads in North America today have a unanimous interest in research toward specific applications in railroad bridge field measurements.
2. Consultants and railroad bridge engineers are also interested in similar approaches by adapting track inspection vehicles toward railroad bridge assessment. There is some previous work relating current track inspection vehicles used by the railroads for specific railroad bridge degradation. In this case, track inspection vehicles inspect and record the change in the track stiffness as they run on the rail. By measuring the change in stiffness from the track, they estimate bridge changes in stiffness. However, this stiffness changes may also include track stiffness changes that may not be caused by changes in the bridge stiffness. Nevertheless, experts in railroad bridge structural engineering pointed out the benefits associated with this approach, as an installation per se is not needed in the bridges, and providing a moveable sensing system that can access all bridges without needing additional mobilization (and demobilization). Recent publications of instrumented freight cars (IFC) used to inspect track geometry describe features and properties of these inspection cars (Meddah et al., 2009), and some structural engineers working for the government and the railroad believe that placing sensors in the IFCs to test the performance of railroad bridges may be of interest for further applied research. In their opinion, measurements of train responses could assist identifying changes in bridge responses, and would consequently assist railroad bridge management programs.
3. During this study, government engineers stressed the importance of providing an automatic sensing system that could be easily installed and removed. They pointed out that this sensing methodology would be beneficial if developed and implemented for railroad bridge inspections. Railroad bridge engineering

experts added that whereas instrumentation of railroad bridges has been typically used in the past for the rating of special bridges, its use toward campaign inspections would be new within the railroad industry.

4. Railroad bridge structural engineers specialized in railroad bridge inspections encouraged researching and developing different inspection data collection tools for different kinds of railroad bridges in a general railroad bridge inspection level. In their opinion, there are many differences in railroad bridges types, and consequently sensing strategies should be flexibly conceived in order to reach all of the railroad bridge types by collecting data of importance to railroad bridges collectively. This group of structural engineers was interested in research toward data collection methods that would be able to adapt to every railroad bridge type.
5. A second group of railroad bridge structural engineering experts believed that railroad bridges applications and strategies should be studied individually and always directed toward a specific railroad bridge type. They explained that although railroad bridge inspectors must know about all kinds of bridges (their territory may contain all RR bridge types), the tools for data collection should be developed for specific railroad bridge types. They added that these data collection technology would more effectively capture particular performance issues specific to that railroad bridge type.
6. A different group of structural engineers with experience in rating railroad bridges expressed significant interest in methods and tools collecting reliable data from railroad bridges. This group of experts showed interest in SHM systems that could send bridge response data to the headquarters office directly. Railroad bridge structural engineer in charge of railroad bridge networks could compare data being collected from different bridges and also at different times. In particular, this group of structural engineers in charge of railroad bridge rating showed significant interest in comparing the evolution of bridge responses over time.
7. Railroad bridge structural engineers in charge of short and medium railroads showed specific concerns toward the use of local data collection systems for global bridge performance assessment. This group of railroad bridge structural engineers thinks that railroad bridge performance data collected locally may not effectively capture global performance of railroad bridges under traffic, so railroad timber bridges performance cannot be assessed by local data collection methods. They explained that data collected locally from timber trestles may not be able to assist obtaining conclusions about the general performance of bridge performance due to their redundancy. They believed that new SHM methods collecting local data performance in railroad timber trestles and obtaining general conclusions about their performance should be studied and developed.
8. Finally, railroad bridge structural engineers showed specific interest in developing sensors that could collect the actual displacement of railroad bridges in real-time. In their opinion, displacement data could be of significant assistance for railroad bridge managers. However, these structural engineers expressed their concern of sensors being able to integrate acceleration records

due to the Rigid Body Motion (RBM) intrinsic effect to the sensor being accelerated. This group of railroad bridge structural engineering experts showed interest in developing sensing tools and methods that can accurately measure real-time displacements of bridges under train traffic, in the three directions (longitudinal, transverse, and vertical).

4.4 Railroad bridge rating

Background of railroad bridge condition and structural rating

This survey-based study has identified so far two potential research topics related to the management of railroad bridges in North America. The first is to understand the inspection of railroad bridges, and the second is to improve the collection of data of railroad bridges under train loads. This research has identified the rating of railroad bridges as a potential topic for railroad bridges and structural engineering research. After the railroad bridge inspection has been completed and the data collected from sensing, if taken, has been processed, the rating of railroad bridges becomes the next step in the assessment of the infrastructure capacity.

Load rating of a railroad bridge is the quantification of the bridge loading capacity in reference to a standardized load value used as a reference. Railroad bridge structural engineers use this standardized reference as a scale for labeling the capacity of the railroad bridges within their inventory. After a railroad bridge structural engineer rates a specific railroad bridge, that bridge rating becomes an indicator or measure of its loading capacity. From that point forward, railroad bridge engineers use this bridge rating in the managing and repair or replacement policies and decisions related to their structural maintenance.

An important aspect of the new FRA rule requiring bridge management programs has been determining the importance of the bridge engineers in determining the actual railroad bridge structural capacity and to include that in their bridge management program (FRA, 2010b).

Yanev studied the importance of structural assessment in different aspects involved in the management of bridges (2008). Yanev's studies proposed a frame space that deals with the design, inspection, liability, and maintenance, as well as an asset of the bridge capacity. Yanev's view of bridge management is shown in Figure 4.8. Yanev, a worldwide expert in bridge management, is currently the Executive Director of the New York City (NYC) DOT bridge inspection and management.

Definition of railroad bridge rating

In 2010 Olson, a bridge structural engineering expert in rating stated that every individual bridge should be able to carry the expected operating load according to the current governing law for that specific bridge. According to the majority of the railroad bridge structural engineers interviewed in this survey-based study, different railroad owners follow a different policy for rating their railroad bridges.

Both DOT agencies and departments and the Federal Highway Administration (FHWA) provide engineering firms and other offices with bridge rating formulas that specify how to calculate the structural capacity of bridges. These formulas traditionally determine the ratio of the loading capacity over the expected loads. According to Olson,

this ratio should be over 1 in order to have a positive rating capacity. The operating ratio is different than the inventory ratio associated with the bridge. According to Olson (2010), the structural properties of the bridge elements may have decayed over the years of service, meaning that sections and thicknesses may have decreased over the years, lowering the structural properties of the bridge (see section 4.2 on railroad bridge inspections).

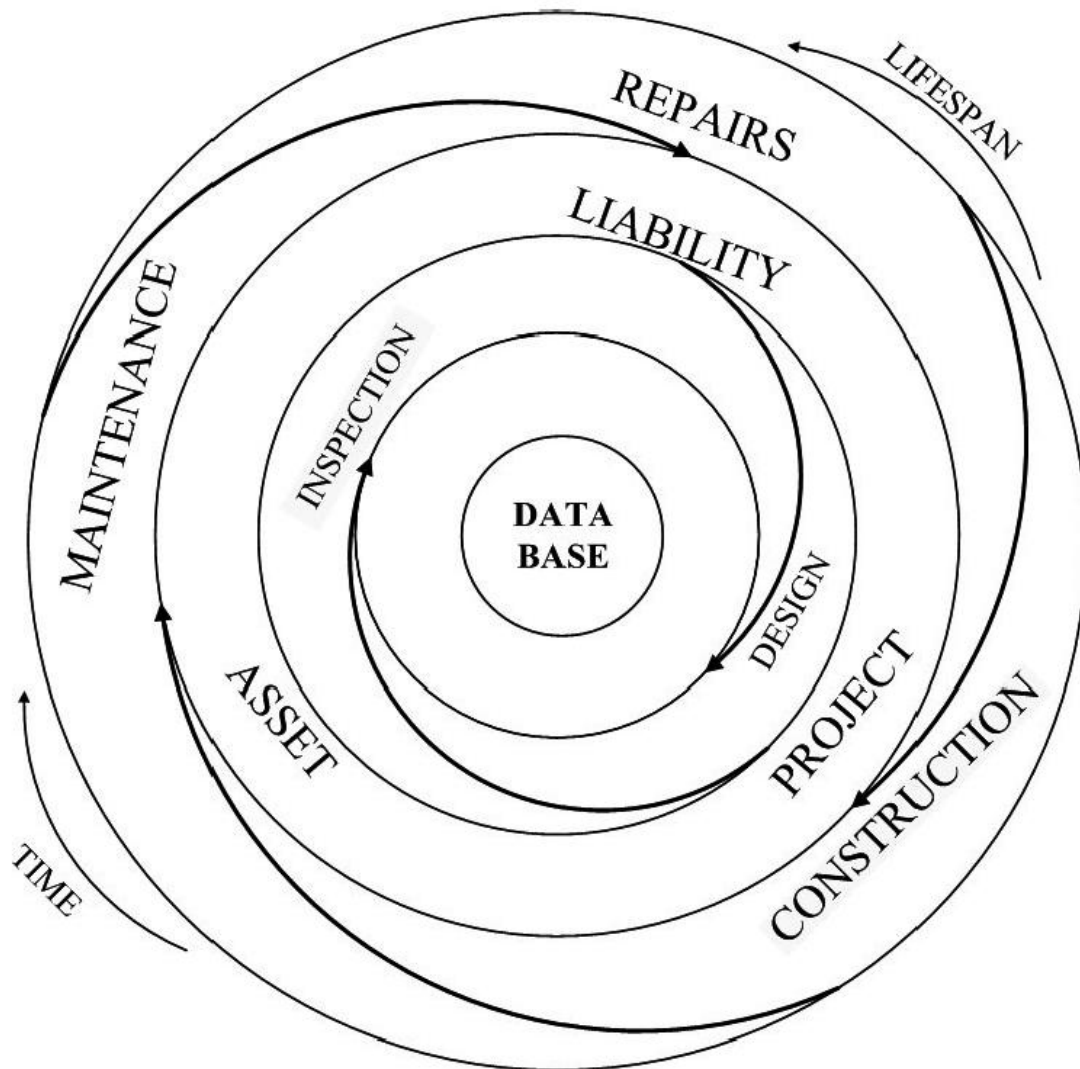


Figure 4.8. The structural lifecycle (Yanev, 2008).

On the other hand, railroads use the E80 Cooper load for rating purposes. This E80 Cooper load has been described in section 3.5. The following example illustrates the way in which railroad bridges are rated today in North America: if a bridge is rated as E90, this bridge could carry loads equivalent to E90 (or 9/8 times the required design load). Another different bridge could be rated as E65, which would mean that that bridge could carry a much smaller equivalent load in comparison with the design load (65/80 times smaller than the design E80 Cooper load). Today, most new Class I railroad bridges

located in railroad main lines are designed for E80 Cooper load. However, some design firms and consulting engineering offices are designing new railroad bridges for E90 Cooper loads.

The following section will outline ongoing discussions related to the rating of railroad bridges as identified during the course of this survey-based study by the different experts in railroad bridges and structural engineering in North America.

Discussion of current topics of concern involving railroad bridge rating

A group composed of both railroad bridge consulting and construction engineering experts stressed difficulties that could be associated with studying rating methods. Furthermore, consulting engineers pointed out their concern in that actual individual rating policies may not be accessible for research and study. A specific group of the interviewees concluded that current rating policies and methods could not be researched and published due to liability issues today.

A sector of railroad bridge structural engineers working for the railroad did not express a specific interest in developing studies related to rating methods or bridge rating during the course of this survey-based study.

On the other hand, new federal regulation (effective September 13, 2010) on railroad bridge safety and railroad bridge management (FRA, 2010a) may change the ways rating of railroad bridges has been contemplated and managed up until today (Paxton Record, 2010). Under this new regulation, railroad bridge owners will have to document the load capacity of their bridges, “together with the method in which the capacity was determined” (FRA, 2010b). The interest in researching and publishing the rating of railroad bridges may be substantially growing today within the railroad bridge structural engineering community, so the possibilities in research and development related to the rating of railroad bridges in North America are listed in the next section of this survey-based study.

Challenges identified involving the rating of railroad bridges

The previous section has shown that there is a potential obstacle in selecting railroad bridges rating as a research topic due to the very private nature of the railroads in North America and the liability potential issues associated with publishing rating methods of railroad bridge departments. Nevertheless, current changes in the way railroad bridge safety is regulated from the federal level have affected the level of exposure of railroad bridge rating methods and formulas. The rating of railroad bridges in North America and the investigation of their tools and methods may be a potential topic for further research and development in the near future. Some of the railroad bridge structural engineers questioned in this survey-based study showed moderate to relevant interest in some specific aspects related to railroad bridge rating.

This survey-based study identifies the following structural engineering research challenges and opportunities related to the rating of railroad bridges in North America:

1. Some of the railroad bridge structural engineers involved in design and construction proposed revising and investigating new methods for the rating of current railroad bridges in North America. In their opinion, and that of other experts working for some Class I, II, and III railroads, sections in the MRE dealing with concrete bridges rating could be further developed. This

group of concrete railroad bridge structural engineering showed interest toward new research investigating new descriptions and methods toward the rating of different kinds of railroad concrete bridges.

2. Railroad bridge structural engineers in charge of consulting and construction activities for the railroad showed interest in developing shear-rating methods for railroad bridges. They suggested researching, developing, validating, and including new formulation and methods for shear rating of railroad bridges in the MRE.
3. Finally, railroad bridge structural engineers involved in short and medium railroads proposed to study new rating methods that better develop timber rating for railroad bridges. Class II and III railroads still have a high percentage of timber trestles in their networks, so the better assessment of their inventories would increase their safety, maintenance and management in general. This group of Class II and III railroad engineers further clarified that the current sections of MRE Chapter 7 dealing with timber (Bridge Structures) (AREMA, 2009) mostly focus on design of new timber bridges. However, this group of engineers added that most needs today are in the management of timber trestles. This study identified during the course of the interviews a notable interest from the North American railroads in the management of timber trestles, so this study now includes a new section entitled “Management of railroad timber bridges in the U.S.” which follows.

4.5 Management of railroad timber bridges in the U.S.

A brief history of timber bridges (trestles) in the U.S.

Timber railroad bridges (also known as trestles) are a critical part of the history of the growth and development of the North American industry. Railroad timber trestles assisted the U.S. toward progress and expansion during the last two centuries. Railroad companies could extend their lines over valleys and flooding basins by quickly building inexpensive trestles to carry steam locomotives and their cars.

Today, railroad trains in North America are in some cases crossing railroad bridges that are about 100 years of age, according to Peterson and Gutkowski (1999). However, most of the railroad bridge structural engineering community agrees that many of the first generation timber bridges are gone today from the main lines of Class I railroads. Nevertheless, Class I railroads (e.g., CN and BNSF) are today using “timber descendants” of those first installed bridges. According to the railroad bridge structural engineers in charge of these two Class I railroads, these railroad trestles are third and fourth generation to the first ones built over 150 years ago. This fact surprises some structural engineers not familiar with North American railroads and who are unaware of the role of timber trestles today in U.S railroad bridge network management. Figure 4.9 shows a timber trestle in Illinois, before its replacement in 2005.

This generation of younger timber trestles (built as recently as 30 years ago) was built with timber of lower quality than the surviving old bridge timber, often with structural properties of higher quality (ignoring decay and other deterioration). However, the construction and quality control used to build and maintain timber trestles have significantly improved throughout the years.

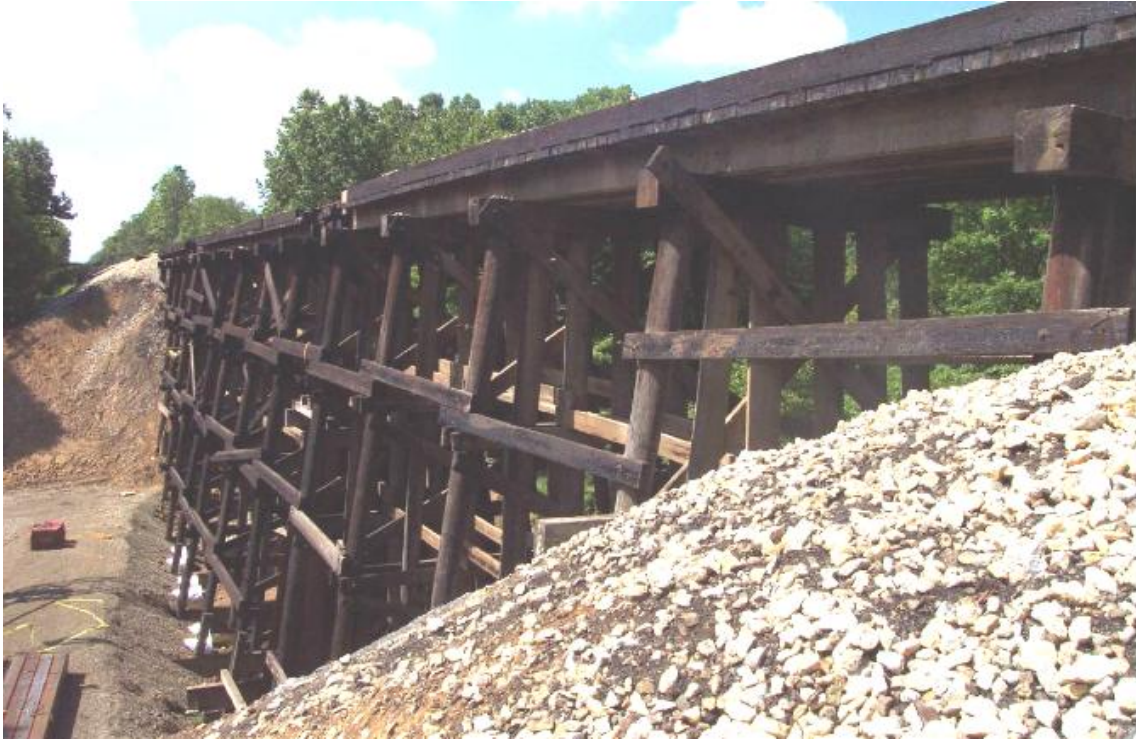


Figure 4.9. Timber bridge in use by a Class I railroad in central Illinois.

In 1996, *Railway Age Magazine* published more than 25% of the total railroad bridge length carrying trains in the U.S. in Class I railroads was made of timber trestles (Anonymous, 1996). This same source pointed out that this percentage dramatically increased for intermediate and small railroad carriers (in which the percentages of timber trestles are higher, surpassing 50% of their inventory) (Anonymous, 1996).

In 2008, the Railroad Bridge Working Group of Railroad Safety Advisory Committee (RSAC), a committee of the FRA, completed a count of the U.S. railroad bridges that can carry railroad tracks. The data was provided by the owners of a majority of the most important railroad companies in the U.S. (FRA, 2008b). The results presented in 2008 are shown in Table 4.3. Based on the percentages shown in Table 4.3, it can be concluded that the performance, assessment and maintenance of timber trestles are of significant importance for the U.S. railroads today. Recent studies about North American railroad timber trestles have pointed out that many of the bridges exceed 50 years of age. These same studies pointed out that exceeding the traditionally accepted 50-year life span for railroad timber trestles is significant (Wipf et al., 2000).

According to some of the railroad bridge structural engineers interviewed during this survey-based study, the design of timber trestles is of marginal interest today, since Class I railroads do not build new timber trestles anymore. However, this same group of experts in timber trestles maintenance pointed out that Class I railroads are trying to replace the remaining timber trestles from their networks with concrete and steel materials.

Another group of railroad bridge structural engineers pointed out that the understanding of design aspects of timber trestles could assist in addressing the behavior, maintenance, assessment, and management of timber members. Additionally, the railroad industry has shown a significant interest in expanding the learning of retrofitting and upgrading of timber trestles, since they are riding their trains over them. Figure 4.10

shows a timber trestle in Kentucky, which was replaced in 2004 by new steel piles with prestressed concrete superstructure (Figure 4.11).

Table 4.3. RSAC Bridge Working Group 2008 bridge count for U.S. railroads (FRA, 2008b).

Railroad classification	Number of bridges	Miles of bridges			
		Metal (including steel)	Masonry (including concrete)	Timber	Total
Class 1 freight	60,688	792.26	368.92	278.02	1,439.20
Passenger	2,129	36.16	17.74	0.24	54.14
Short Line & regional	14,033	106.64	20.24	140.01	266.88
GRAND TOTAL	76,850	935.05	406.90	418.27	1,760.22
1993 percent		47%	17%	36%	
2008 percent		53%	23%	24%	



Figure 4.10. Timber trestle in use by a Class I railroad in Kentucky.

Definition of “timber trestles” in U.S. bridges

As discussed before, timber trestles are part of the prosperous growth of railroads in North America during the last 150 years. Table 4.3 shows that railroad timber trestles are also critical elements of railroad bridge networks. Proper understanding and management of timber trestles are critical to the future of North American railroad networks present and immediate future.



Figure 4.11. New Class I railroad bridge viaduct replacing a railroad timber trestle in Kentucky.

As explained by some of the railroad bridge structural engineers experts in railroad timber trestles management, Class I railroads today use their own standards followed for the design and construction of timber trestles. With these standards, the railroad industry ensures a sustainable maintenance of their elements over time. The main section of a timber trestle deck (which is a standard deck) is in general supported by the same standard section of stringers, pier caps, and timber piles, regardless the height of the bridge in study. The bracing between the piles varies from bridge to bridge, but the section properties of the members (geometrical dimensions, strength of materials) are generally the same, as this group of structural engineers pointed out.

In general, the pile driving records of each railroad bridge may not remain with each bridge's records, if the bridges are old and the pile driving records were lost over time. It could also be the case that the pile driving records were not properly documented. Their reliability has depended on specifics of railroad regions, territories, and structures & bridges departments. It is not uncommon to lack information regarding actual properties of a bridge under study due to the lack of pile driving records, according to a group of railroad bridge structural engineers interviewed in this survey-based study. As pointed out in previous sections, the current FRA regulation (2010b) will have a significant impact on the way bridge construction records are kept (for railroads of Class I, II, and III), in the sense that even when railroads may not have pile driving records available for a specific railroad bridge, they now will have to provide alternative ways to obtain the same information (that would have been easier to get from the original construction

records). The new FRA regulation will directly promote better record-keeping for all railroad bridges in the U.S., including for management of timber trestles.

Railroad bridge structural engineers would like to have better ways to assess the foundation depth and properties of timber piles supporting timber trestles, since this information is in many cases unknown by the railroads. This group of structural engineers pointed out that timber piles are in fact a very critical unknown piece of information for determining bridge structural engineering properties. They added that successfully identifying timber pile foundation properties plays a critical role in deciding whether timber trestles should be replaced or not, and by which kind of new bridge.

Current discussion involving railroad timber trestles in U.S.

Besides these general problems stated above, there are other factors associated with railroad timber trestles that in addition would need to be considered in order to correctly understand their role and criticality to today's railroad network safety and reliability as a whole. For example, Figure 4.12 shows the accumulation of debris upstream of two different railroad bridges. The standard spacing between piers in timber trestles in North America is 13 ft (4 m). This span cannot be increased for a typical deck composed of a typical sequence of stringers with standard sections. Heavy rain or other sequence of weather related events seasonally bring an accumulation of debris that cannot run downstream between that tight standard pier spacing. Figure 4.13 and Figure 4.14 show the replacement of timber trestles with DPGs as a solution to this problem.



Figure 4.12. Debris accumulation on tall timber trestles after seasonal rains.

Traditionally, railroads have maintained their bridges removing the accumulation of debris by using their own maintenance of way forces, or by contracting consultants and contractors. The new working environment and the new different ways of running railroads try to limit maintenance costs and reduce safety hazards when possible. Railroads are trying today to increase the spans of old timber bridges by entirely (or partially) replacing them. In this way, railroads try to build new bridges that are stronger and safer with reduced maintenance costs. This is a good example on how the reliability of railroad networks can be improved by understanding properties and particularities of their timber bridges in use.



Figure 4.13. Typical timber trestle upgrade by DPGs on concrete abutments (phase I).

According to the experts in railroad timber trestles in North America, it is important to understand not only the weak points of timber trestles, but also their virtues for the timber for the railroad industry. If timber was not a good material, it could have not lasted all this time carrying railroad trains in North America. It was pointed out during the course of the study that today, even when North American railroads want to move forward and replace their entire inventory of timber trestles with new materials as soon as their budgets allow, it is worth noticing how well timber has lasted.

The experts in railroad timber trestles have explained that timber trestles are carrying trains today, even when the loads they were designed to handle have increased dramatically, and although many stronger heterogeneous materials have become available in the last century. This survey-based study has identified the main reasons timber trestles are still being significantly present in North American railroads today, and these are listed below:

1. From the railroad owner's perspectives, timber bridges are very easy to maintain, according to some railroad bridge railroad structural engineering managers interviewed. They supported their statements by explaining that individual elements could be replaced without putting the bridge out of service, because timber trestle elements are short and can be removed and replaced with adequate crews and machinery used by the railroads for over a century. Specialized replacement equipment that operates from the railroad track can, for example, replace a pier cap from the track level.



Figure 4.14. Typical new DPGs replacing an old railroad timber trestle (phase II).

2. According to some railroad bridge structural engineers involved in timber bridge rating, timber trestles are extremely redundant structures. Their redundant standard design and concept could typically provide sufficient notice to railroad bridge inspectors of the degradation of bridge responses over time. Timber bridge structural engineers pointed out that these signs would warn engineers for implementing actions towards bridge maintenance prior to catastrophic collapses expected from railroad bridges built with less redundant structures (e.g. prestressed concrete beams).
3. A group of railroad bridge structural engineers working for the railroad pointed out that timber bridges are cheaper than bridges built with other materials. Railroads are private companies that will invest only the amount of money required to have the biggest benefit associated with that investment. According to this group of structural engineers, 50 years from now the business scenario could be very different from today. Railroads have preferred to invest in less expensive materials/techniques with shorter lives (50 or even 30 years) rather than invest larger amounts of capital for unforeseeable future scenarios (75 years is considered a very long time by the railroad industry).
4. Another group of railroad bridge structural engineers interviewed in this research pointed out that timber is less stiff than other materials like steel or concrete. They explained that the flexibility of timber has sometimes become beneficial to the railroad industry from the maintenance point of view. In particular, the flexibility of railroad bridges allows the assessment of the performance of timber trestles under railroad traffic better than any other

materials by visual inspections. Large displacements that may be obvious in railroad bridges could go unnoticed with different bridge materials under similar stress levels. Refer to section 4.2 on railroad bridge inspections to learn more about current visual inspection procedures for railroad bridge maintenance.

5. Railroad bridge structural engineers' experts in seismic performance of railroad bridges pointed out that there is little documented research involving the performance of railroad bridges under seismic excitation. This is in part due to the better performance of such bridges in small to moderate earthquakes than highway bridges. Some studies exploring the seismic performance of bridges propose the need for further research in this direction (Mander et al., 2000; Shama and Mander, 2003). According to Chris Poland, an expert in structural engineering and earthquake engineering, there is a great need for academic research about the seismic design and performance of railroad bridges (Poland, private conversation, 2009).
6. Finally, timber bridges are easy to remove and replace, since their structure can be easily turned down with conventional construction machinery. This is a good property for a railroad when a new investment or improvement is required. The amount of time that a railroad can shut down their specific route to allow a new bridge to be built should be always maintained to a minimum. Having a quick and easy to remove bridge helps significantly the replacement operations. At these times, timber bridges are greatly appreciated because their intrinsic fragility meets the quick replacement needs of the railroad industry. Figure 4.15 shows the timber trestle replacement with a DPG executed in a total work window of just twelve hours, including the turn down of the timber section and the erection of a DPG. The last train crossed the timber bridge at 6:40 A.M. and the first train crossed over the DPG at 6 P.M. on the same day. The time invested in the timber portion removal to accommodate the new DPG was limited to 3 hours. Figure 1.1 of this report (see page 3) shows a picture of the same bridge replacement at 1 P.M., while Figure 4.15 shows a picture taken at 10 A.M. that same day.

The previous sections have described the main properties and particularities of timber trestles as critical elements of the U.S. railroad bridge inventory. The following section compiles suggestions from the railroad bridge structural engineering community represented by the interviewees of this study in regard to railroad timber trestles and the potential research topics that would be of interest from the railroad industry's perspective.

Challenges identified related to timber trestles in U.S.

This survey-based study identifies the following structural engineering research challenges and opportunities related to railroad timber trestles in North America:

- 1) Both consultant and AAR railroad bridge structural engineers interviewed during this survey agreed in the importance of understanding the way timber trestles decay to help railroad owner in their inventory management. There are still many railroad timber trestles in use that need to be assessed better, some of the senior railroad bridge structural engineers pointed out. Railroads will

continue replacing their entire population of timber trestles with bridges made of new materials. However, there are still many timber trestles in use, and research in their performance is encouraged and needed by railroad bridge structural engineers in charge of management.



Figure 4.15. Timber trestle replacement in Cruse, Illinois.

- 2) A group of railroad bridge structural engineers emphasized that they would like research addressing the performance of timber bridges under current train traffic. These structural engineers proposed the creation of certain tables that match different timber bridge elements (size, length, mechanical properties) and the response levels associated to those, within a certain factor of reliability. Research enabling a correlation between timber member properties and their performance under traffic would be of great interest by the railroads, according to this sector of interviewees.
- 3) Another group of railroad bridge structural engineers would like to develop Non-Destructive Testing (NDT) that could help assessing timber elements in the field. Today, according to this group of experts, these properties are determined with boring techniques. These timber assessment methods take time and demand specially trained labor forces and equipment at considerable expense to the railroads. Research and development in NDT methods for timber bridge elements would help railroad bridge engineers in charge of determining actual capacity of their trestle inventories. As explained previously in this report, FRA's new rule (FRA, 2010b) on railroad bridge

safety requires all railroads (Class I, II, and III) to know the load capacity of their bridges.

- 4) Some railroad bridge structural engineers proposed developing NDT techniques that could be employed to identify the depth and quality of existing timber foundations. Even though they are not included in the timber trestle category, timber foundations are of great importance for railroad bridge owners because they provide support for current medium and long span North American railroad bridges that are over 100 years old (see Figure 4.16). Identifying the capacity of timber foundations is of great interest of railroad bridge managers. The depth and quality of railroad bridge piles is an important amount of information for the owner for two reasons: (1) it helps determining the foundation capacity of a specific bridge, and (2) it helps to understand and identify the actual bridge site conditions to successfully determine and design the right retrofit (or complete new bridge) for that specific site. It is not always possible to find as-built drawings from bridges that were built in times more than 50 years ago and are still in service, as it was pointed out previously.

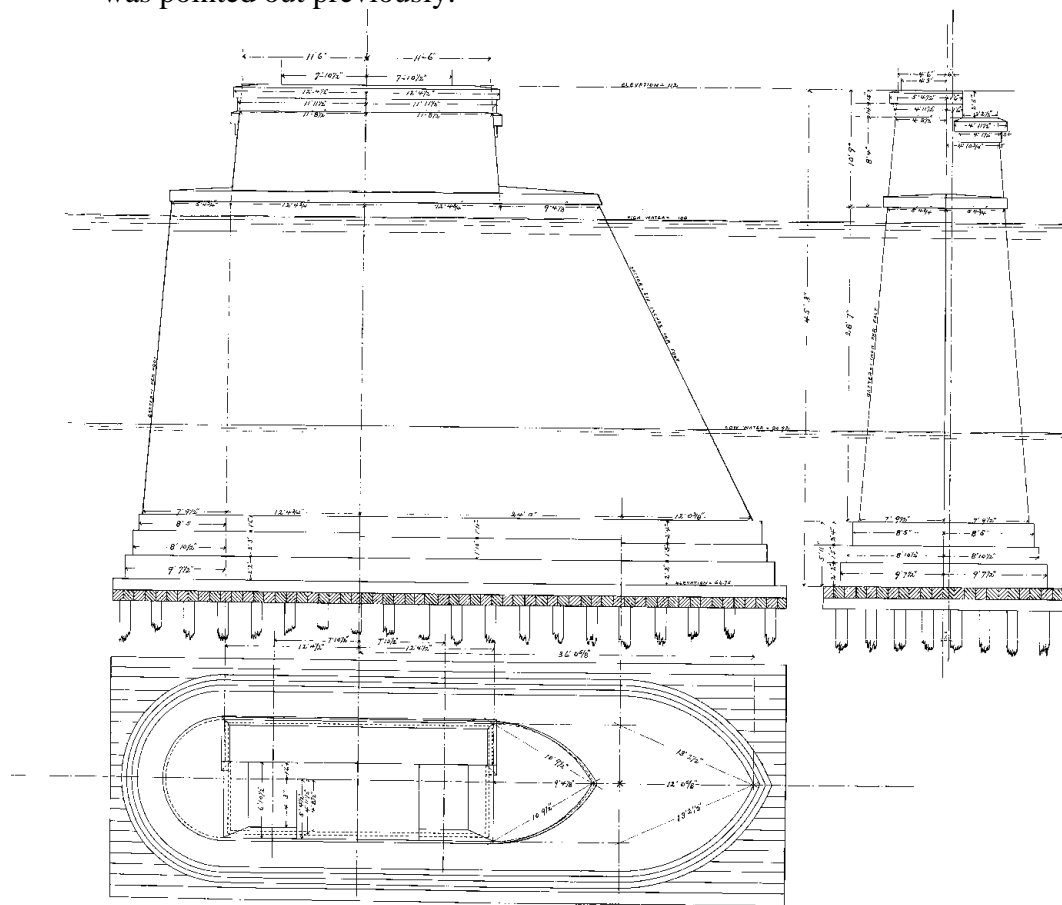


Figure 4.16. Masonry pier foundation on timber piles (1867 bridge at the Mississippi river, with a traffic today of more than 30 trains / day).

- 5) A significant group of the railroad bridge structural engineers interviewed in this research pointed out their concern regarding scouring. As they pointed

out, scouring undermines the foundation of railroad bridges due streams and currents affecting railroad bridge foundations by changing the soil conditions in which the bridge is being supported. This group of experts expressed specific concerns toward the effects of scouring in timber trestles and deep foundations, and indicated particular interest in studies and research that develops new ways to monitor and assess railroad bridge integrity and robustness during and after scouring events. Figure 4.17 shows timber trestle scouring caused by high current conditions generated around the existing timber foundation, affecting the soil conditions supporting the timber trestle.

- 6) Several railroad bridge structural engineers interviewed in this survey-based study pointed out past and current studies carried out by universities determining the actual capacity and performance levels of timber elements (Wipf et al., 2000). Nevertheless, this group of railroad bridge structural engineers agreed that further studies devoted to improving rating procedures of timber trestles would be beneficial, especially for short and medium class railroads in light of the new FRA regulation (FRA, 2010a, 2010b).
- 7) This survey-based study has found out that bridge structural engineers working from Class I railroads seemed more interested toward the specific performance of timber elements in bridges like pier caps. On the other hand, bridge structural engineers working for medium and short lines seemed more interested in the development of guidelines that assist them in addressing bridge capacity levels and categories for managerial purposes.

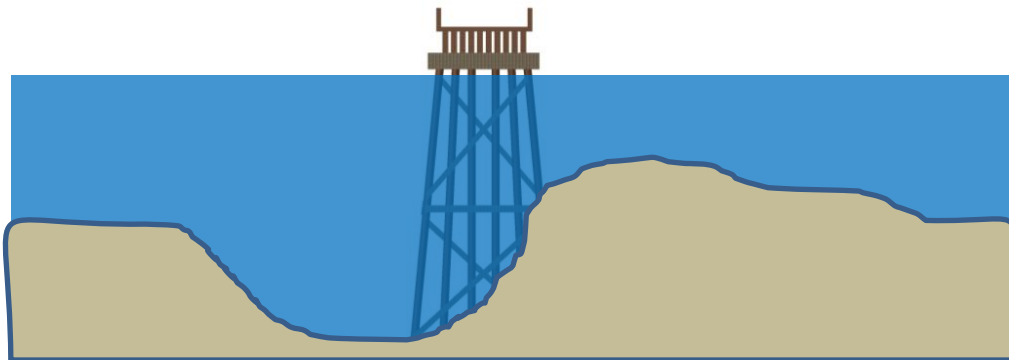


Figure 4.17. Scouring of timber trestle due to high current affecting soil conditions around the bridge foundation.

RAILROAD BRIDGE MAINTENANCE AND CONSTRUCTION

5.1 Introduction

In 2007, an article entitled “US railroads inspect, maintain bridges mostly by themselves, GAO report says” (Miller, 2007) indicated that the FRA authorities considered that the way railroad bridges were inspected and maintained up to that date was satisfactory. The article concluded that the FRA considered railroad bridges to be currently in good conditions for the most part.

However, that same year, Kube published in *Trains Magazine* an article entitled “Bridging the gap” (Kube, 2007). In Kube’s article it was noted that on September 11, 2007 the FRA issued Safety Advisory 2007-03 recommending railroads to adopt specific changes to ensure that their bridges were safe. In fact, the FRA recently turned their ongoing efforts into the new regulation discussed in Chapter 4, Railroad bridge management (FRA, 2010b). Additionally, past regulations published by the FRA (2000, 2002) reflect continuous efforts toward bridge safety and management.

Most of the structural engineers asked during the survey coincided in the criticality and importance of railroad bridges maintenance today. Top structural engineers interviewed during this survey-based study placed railroad bridge maintenance issues at the top of their request for conducting research in railroad bridges. Some of the research topics related to maintenance identified in the course of this survey-based study included the following:

- 1) Economic studies of railroad bridge maintenance:
 - a. Economics of timber trestle maintenance versus timber trestle replacement.
 - b. Long span (truss) bridges maintenance versus new long span (suspension) bridges replacement.
- 2) Studies and new methods of construction and replacement of railroad bridges: methods to build and repair bridges under traffic reducing interruptions to trains.
- 3) Developing new inexpensive methods for railroad bridge data collection under train traffic: obtaining information from bridges under traffic for maintenance/replacement prioritization. Quantifying the railroad bridge capacity from measurements taken in the field under train traffic.
- 4) Study and develop new bridge approaches for railroad bridges. Research methods that propose new ways to replace and maintain railroad bridge approaches.
- 5) Study better ways to extend the structural life of existing railroad bridges.
- 6) Assess and measure the performance of long term welds in railroad bridges.
- 7) Adaption of non-destructive inspection techniques for timber bridge maintenance.

- 8) Estimating the capacity of an entire railroad bridge structure when and/or if secondary elements are removed from the railroad bridge.
- 9) Estimating the entire capacity of a railroad bridge as opposed to providing the structural capacity of one single element of that railroad bridge.
- 10) Relate inspection and maintenance operations and new proposals to the actual track maintenance programs and machinery available in railroad companies.

As shown in Figure 5.1, the replacement of elements is an important aspect of maintenance of railroad bridges in North America. This figure shows the partial replacement of different elements of a railroad bridge. Specifically, the deck slabs and backwalls were replaced while the railroad decided to keep the same existing substructure.



Figure 5.1. Maintenance results in a 100 year old railroad bridge superstructure replacement, while keeping the substructure, which was found in good condition.

Railroads decide in numerous occasions to replace their bridges because the costs associated with their maintenance increase beyond a certain level in which it is estimated replacing the entire bridge would become more economic. In the railroad industry it is rare to have a sudden failure in a bridge caused by the structural deterioration or decay of a member, some of the experts in structural engineering in this survey-based study pointed out. As a consequence, the maintenance of railroad bridges plays a critical role for the day to day operations and decisions of railroad bridges structural engineers. The maintenance of railroad bridges involves a close understanding of the bridge members and elements and also of the bridge performance under life loads. It is in this line of thought that monitoring and instrumentation can effectively reduce maintenance costs (Lee et al., 1999). Section 4.3 contains further details about current structural engineering research topics related to the data collection of railroad bridges.

During the course of this survey-based study, the importance of various specific aspects related to bridge maintenance was stressed. Different specialists in structural engineering and railroad bridges determined several topics related to maintenance of railroad bridges that are included in this section. The following sections collect the different structural engineering research topics related to the maintenance of railroad bridges in North America that were gathered during the course of this survey-based study.

5.2 Prioritization of member replacement for railroad bridges

Several railroad bridge structural engineers interviewed during the course of this survey-based study identified the importance of determining the actual capacity of individual members within the structure to safely and economically maintain railroad bridges. In their opinion, deciding which bridge elements should be replaced first in a bridge is of paramount interest of structural engineers in charge of maintaining railroad bridge networks. This is particularly true since their decisions need to be made within a limited budget.

This survey-based study identifies the following structural engineering research challenges and opportunities related to the prioritization of member replacement for railroad bridges in North America:

- (1) Improving specific bridge member inspections and actual member capacity assessment
- (2) Enhancing rating methods for both concrete and timber railroad bridges
- (3) Developing NDT specific to timber and concrete members of RR bridges
- (4) Developing new soil inspection techniques that could improve the understanding and the identification of the piling length and quality of timber piles

Figure 5.2 shows the replacement of a timber trestle with PC beams and one DPG. The railroad decided to use five different work windows for the replacement: two (2) for both end backwalls, two (2) for both approaching PC slabs, and one (1) for the central DPG. The definition of “work window” is presented below.

5.3 Rapid bridge replacement current practice and techniques

Because interruptions to traffic must be minimized, railroad bridge replacement and maintenance operations are dramatically shorter than those for highway bridges. This is mainly because railroad traffic cannot be diverted when bridges are being repaired. Railroad owners and clients agreed in this survey-based study in emphasizing that long disruptions to their traffic would imply unbearable costs. Railroad bridge structural engineering experts defined interruptions to traffic caused by bridge replacements as “change-outs.” The allowed time to have traffic diverted or stopped is called a “work window,” and should be kept to a minimum (Moreu, 2007; Keane, 2007). Figure 5.3 shows a work window.

Railroad bridge structural engineering experts showed great interest toward researching new techniques, materials, control systems or concepts that better control and reduce the time of work windows. Railroads are investigating new rapid superstructure

change outs, such as cranes accessing and replacing beam elements from the track (Markelz, 2010). According to this survey-based study, the safety of the staff involved in railroad bridge change-outs would also benefit from new advancement in this area, since work windows are very intense operations for all labor, transportation and equipment. Finally, the use of prefabricated bridge elements is a key element to rapid bridge replacement (Moreu, 2008; Russell et al., 2005). Studies of further development and use of prefabricated elements for railroad bridge quick replacements is also of significant interest for research by railroads, according to this study. In the highway bridge engineering community, this topic is typically referred as Accelerated Bridge Construction (ABC).



Figure 5.2. Partial replacement of a timber trestle railroad bridge in the Midwest of U.S.

5.4 Robustness of existing railroad bridges

A group of railroad bridge structural engineers pointed out that determining the actual capacity of railroad bridges elements and bridges is critical to any action related to bridge maintenance (including replacement, repairs, and upgrading). This group of experts pointed out that railroad bridge engineers need to quantify actual bridge strength capacities available for their bridges in the field. According to these engineers, a big priority and interest of railroad bridge departments is to assess the structural capacity of the bridges, or at least to ensure their integrity. Figure 5.4 shows the testing of cylinders taken from repaired railroad beams. This testing was performed in order to determine the actual bridge strength available at the field. However, as the railroad bridge structural engineers clarified during this survey-based study, testing (and modeling) cannot provide

the actual bridge capacity available in the bridge, and furthermore, it often takes time sometimes not available during urgency situations. Sometimes information needs to be readably available to be used quickly and efficiently by the railroad bridge structural engineer in charge of that railroad bridge.



Figure 5.3. Backwall installation for a work window between trains.

Railroad bridge structural engineers interviewed in this survey-based study prioritized research that explores developing new methods that can assist determining railroad bridges integrity. They further expressed interest in methods that can be quickly used by either railroad bridge inspectors, or alternatively already assembled tools that allow quick decision-making by railroad bridge structural engineering managers. Railroad bridge structural engineering experts in North America are interested in means and methods that can quantify bridge integrity from field measurements, and also in technologies or tools that could assist railroads to determine the integrity of their bridges under unexpected situations.

Finally, past studies related to the estimation of railroad bridge integrity identified quantifying capacity of bridges or bridge elements as an area of great interest for railroads owners, consultants, and contractors (Anonymous, 2006). Similar studies by El-Tawil (2004) concluded that measuring the performance of railroad bridges would be of great value for railroad bridges.

Railroad bridge scour

This survey-based study has identified the scour of railroad bridge foundations as a particular topic of interest for research and development. According to a group of railroad bridge structural engineering experts interviewed in the course of this survey-based study,

scour is the top emergency condition in which railroads need to quickly assess the capacity of their bridges. Scour refers to the undermining of bridge pier foundations capacity caused by a change in the soil conditions, generally caused by strong currents under flooding events. This is not a surprise for structural engineers involved with highway bridges, since according to Allampalli (2009), up to 56% of the highway bridge failures in U.S. highway bridges are caused by hydraulic causes, as shown in Figure 5.5. On the other hand, Figure 5.6 illustrates the evolution of scour for a typical railroad bridge pier.



Figure 5.4. Concrete samples testing in the laboratory for a Class I railroad to validate concrete repairs in the field.

Several researchers have studied scour over the years as it relates to the health and integrity of railroad bridges and it causes traffic disruptions. In 2002, the FHWA sponsored research toward the understanding of scour monitoring methods (Nassif et al., 2002). In 2005, research developed by Olson (2005) (sponsored by the FHWA) evaluated and monitored the dynamics of bridge substructure. Briaud et al. (2011) conducted laboratory and field experiments to research the real-time monitoring of bridge scour with remote monitoring technology. Suzuki et al. (2007) and Masato et al. (2010) studied means and methods of measuring railroad bridge integrity after scouring events.

This survey-based study concludes that there is a significant interest in the railroad bridge structural engineering body to conduct and develop studies and research that can find inexpensive and practical tools to address current concerns related to railroad bridge integrity caused to scour.

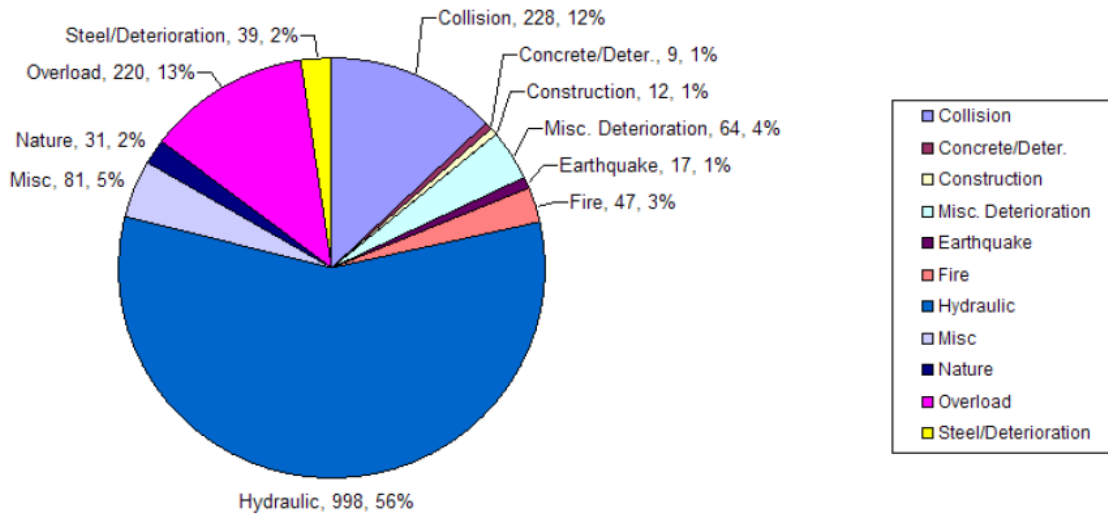


Figure 5.5. U.S. Highway bridge failures (Allampalli, 2009).

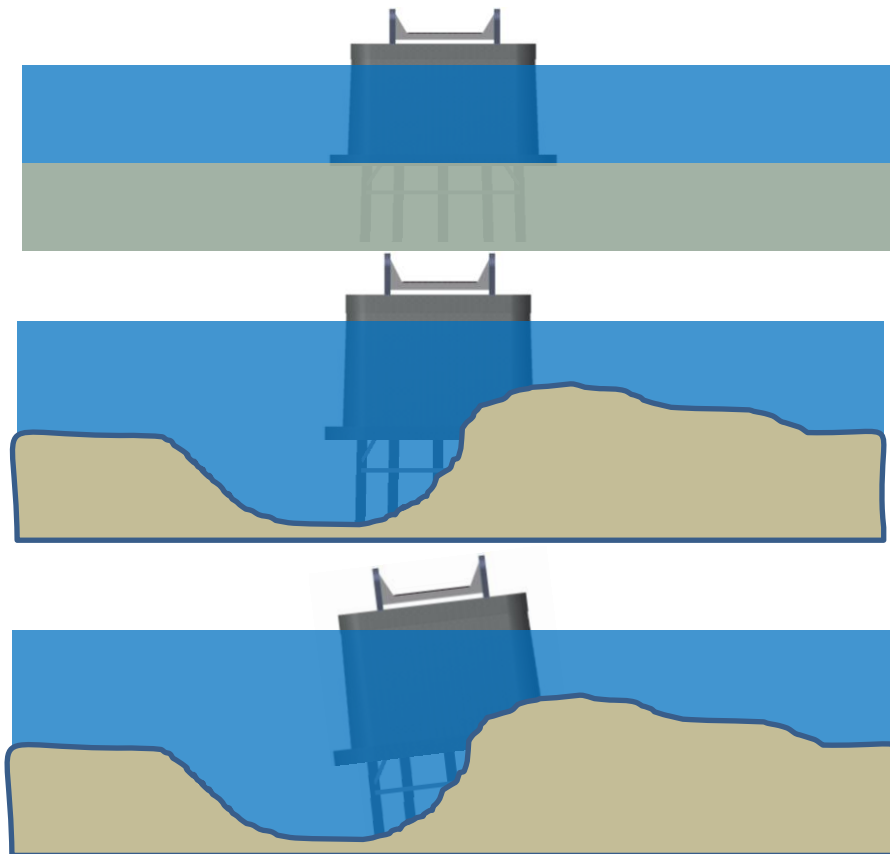


Figure 5.6. Scour of a railroad bridge.

5.5 Current practices to extend the life of railroad bridges

According to the railroad bridge structural engineers interviewed in this study, those structural engineers managing railroad networks have to make decisions about the extension of the life of bridges. In particular, these structural engineers would like to avoid railroad bridge replacements if they could prove that they would not be needed. Thus, they would reduce the amount of time a railroad line is interrupted, as well as the amount of money that would need to be invested in a brand new railroad bridge. Once the capacity of the railroad bridge has been determined in the field, the bridge strength lacking can be estimated. Based on that assessment, a bridge repair needs to take place. Figure 5.7 shows the work in a partial replacement for a railroad bridge in which the central span was replaced by new steel piles that needed to be collared in order to provide a solid foundation.

This survey-based study identifies the following structural engineering research challenges and opportunities related to extending the life of railroad bridges in North America:

- (1) Researching new replacement techniques and materials for railroad bridges
- (2) Testing new evaluation methods that could assess bridge capacities more accurately and thus quantify bridge capacity. Interviewees explained that replacements would be then justified from a strict understanding and knowledge of their field structural capacity
- (3) Develop monitoring techniques for bridge capacity assessment during bridge upgrades and retrofitting operations (Schuyler and Gularte, 2000)



Figure 5.7. Concrete collar installation in a maintenance intervention for a railroad bridge partial replacement (Class I railroad).

5.6 Economic approach to railroad bridge replacements

Figure 5.8 shows a complete bridge replacement operation for a two-track railroad bridge at a highly congested line in the U.S. Great Lakes Region. The previous timber trestle was moving in excess under normal traffic loads. In order to attenuate the movements of the track over the bridge, the railroad have slow orders to traffic and regular works of repair and maintenance. Both the slow orders to traffic and the bridge maintenance duties were becoming costly and also unsafe from the railroad perspective. The financial investment in the replacement was justified. As many railroad bridge structural engineers interviewed in this survey-based study, it is mostly the cost associated to the slow orders and maintenance that governs bridge replacements, rather than the fear of a bridge collapsing under an excessive demand. Railroads currently take the replacement decisions on bridges based in a maintenance cost approach policy. Railroad owners are interested in quantifying the cost of bridge replacements based in the actual structural capacity of the existing bridge inventory. Railroad bridge structural engineers would compare bridge capacities to prioritize bridge replacements. Methods of comparing bridges and bridge elements to each other in order to better determine which bridges or bridge elements would need to be replaced first would be of great interest for the railroad bridge structural engineering community, according to this survey-based study. For example, TTCI (AAR) has already produced research linking the economics of imbalanced loads on bridges (Joy et al., 2008), as it was published in the *Technology Digest* April 2008 (TD-08-014).



Figure 5.8. Complete railroad bridge replacement in a main line with more than 26 trains/day (no work windows allowed).

OTHER TOPICS

6.1 Introduction

This survey-based study has identified during the course of the interviews additional research topics in railroad bridges and structural engineering that were not initially included in the original list of questions. In some particular occasions during the interview process, different people asked at different times suggested the same research topics. In addition, during the literature review process, studies about these same research topics were found. Finally, conversations and presentations from recent conferences and seminars involving railroad engineering also covered some of these research topics.

These professional meetings included:

- (a) AREMA annual conference and exposition, Chicago, Illinois September 20 to 23, 2009
- (b) 15th Annual AAR research review, Pueblo, Colorado, March 2 to 3, 2010
- (c) AREMA annual conference and exposition, Orlando, FL August 29 to September 1, 2010
- (d) AREMA Committee 10 meeting, Saint Louis, MO June 21 to 22, 2011

The final list of “other topics” was composed by prioritizing those research areas of higher importance. The criterion to select the final list of topics was grounded in the following considerations:

1. The uniqueness of the topic: if the research topic is particularly singular, then conducting research about this new topic for railroad bridges and structural engineering should be encouraged and included in this survey-based study.
2. The innovative nature of the suggestion or idea for research: studying new research topics may lead to the development of new research paths that could be implemented in the railroad bridge industry, and that should be promoted and supported for research.
3. The relationship of these new topics to other areas already being investigated or already brought up by other participants of this survey-based study.
4. The potential of the new research topics to be included in projects that may become of interest for research towards other types of academic or consultant activities, even when these topics may not have the contents or challenges to eventually become thesis materials for PhD studies.

The sources for the research topics included in this section have been described, along with the criterion to which the new research topics were selected to be included in a new section called “other topics.” Finally, the following six sections describe “other topics” that were gathered during the interview process of this survey-based study. The following six research topics included in the section “other topics” did not qualify to be included in the previous sections because of one of the following two reasons:

1. They did not qualify to be included in the predefined sections as specific research topics directly related to:
 - a. Design

- b. Maintenance and Construction
 - c. Management
2. They could not be included as a specific section because they lack at least one of the following:
 - a. A current or direct exposure to the railroad industry in the research front as of today
 - b. A clear and direct potential for use by railroads in the United States in a near future
 - c. A specific and well defined methodology or unique approach. In some cases, because they have been widely studied in the past and they would need to be covered in lengths exceeding the goal of this study

The following six sections present other research topics or areas for study that were presented or found in the course of this survey-based study. Different railroad bridge structural engineering group of professionals suggested their consideration for future research studies and justified their interest and motivations, as it is explained in the following pages.

The potential research topics in railroad bridges and structural engineering identified in this survey-based study classified under “other topics” category are:

- New materials for railroad bridges
- LRFD adaption for the design of railroad bridges
- New steel bridge standards development
- Finding railroad bridge damage (local damage detection)
- Fatigue in railroad bridges: current topics
- Seismic studies and topics related to railroad bridges in U.S.

6.2 New materials for railroad bridges

During the course of the survey-based study, several railroad bridge structural engineers pointed out their interest in researching new materials for the design and construction of new bridges and in developing new materials that could ease and hasten the replacement of existing railroad bridges. The interest in new materials for railroad bridges in North America is not a novel concept. There have been recent studies and practices within the railroad industry exploring and even using composite materials for new railroad bridges. At the 2010 AREMA conference, Kim presented to the audience of experts in railroad bridge structural engineering the first railroad plastic bridge (Kim et al., 2010). This topic and presentation raised several questions in the audience of experts. In particular, railroad bridge structural engineers inquired after Kim’s presentation about the flexibility and durability of the new material. The impact and details of this ARMY Corps of Engineers new bridge have been documented in several other publications, as Businesswire, given the novelty of the concept and the potential impact in the railroad business (Businesswire.com, 2010).

In recent years, TTCI (AAR) has supported research toward the use of hybrid-composite beams for railroad bridges. The following the former example of using new materials for railroad bridges and the research and testing associated with it.

In 2008, AAR tested a bridge built with Hybrid-Composite (HC) elements at Pueblo, Colorado (see Figure 6.1). In 2002, Innovations Deserving Exploratory Analysis (IDEA),

for the TRB in Washington D.C. started helping this research by providing funding and support at the early stages (Angelo, 2008). The new railroad bridge superstructure used in this testing was made with Hybrid-Composite Beams (HCB).

There are several motivations within the railroad industry for exploring the use of composite materials in railroad bridges. The main interests from railroad companies toward research of new materials for railroad bridges are outlined below:

1. The weights of composite materials weights are lighter than other traditional materials used for railroad bridges (such as concrete and steel). Superstructure elements made of composite materials could span larger distances with less weight, as pointed out by Class I railroad bridge structural engineers during the survey.
2. Additionally, recent/positive experiences using composite materials by DOT's have generated an increasing interest towards the use of these materials within the railroad bridge structural engineering community, as some consultant structural engineers stressed during the course of this survey-based study.



Figure 6.1. John Hilman showing his Hilman beam under railroad traffic at FAST (Pueblo, Colorado) (Courtesy of HC Bridge Company).

3. Many North American railroad bridges have limited access (with the exception of rail access), some of the experts in railroad bridges and structural engineering pointed out. Railroad companies need to invest large sums of money to ease the access to these railroad bridge sites. This becomes more expensive with railroad bridge projects requiring large and heavy bridge elements. The use of lighter elements for longer spans is welcome by railroad companies in North America. In

the opinion of some railroad bridge departments and their personnel, using light bridge elements to replace existing railroad bridge elements would allow using the in-house erection machinery from railroads. Additionally, using lighter elements would allow bridge replacements to be performed from the railroad track (as it was earlier described in point 1 of this list.)

Chuck Taylor, Program Officer for the IDEA Program, described: “Our rail infrastructure is in many cases nearing the end of designed life so this comes at a critical time.” In this context, Taylor added: “HCB shows real promise as a cost competitive alternative to steel and concrete beams” (Angelo, 2008). Hilman Composite Bridge Company has published results and findings regarding advantages and disadvantages in using this new material (HC Bridge Company, 2010). As described in the Website of HC Bridge Company, the Hilman Composite Beam is a registered patent in the United States (U.S. Patent 6,145,270; HC Bridge Company, 2010).

Another article published in *MassTransit* (Anonymous, 2008) also coincides with the remarks pointed out in the *Engineering News Record* (ENR). These two publications pointed out the potential and interest today of transportation agencies in supporting research directed towards new materials. In particular, transportation agencies are interested in new ways and developments that could improve the way bridges are designed and constructed today. They would be interested in research and development toward innovative and creative study of materials that could be used in bridges design and construction.

Officers from the TTCI (AAR) started testing these beams in 2008. According to Angelo (2008), TTCI (AAR) fulfilled their expectations up until the date. In their notes, this new material has been proven to be a real alternative to the traditional concrete and steel railroad bridges that are typically contemplated when improving the existing network.

In past years, the introduction of new materials in the railroad industry has been proven to provide advancement in the construction, planning and maintenance of the entire network (AAR, 1967). Further studies in this direction could benefit the understanding and evaluation of this new material as a real alternative for railroad bridge industry.

Additionally, in the course of this survey-based study, Duane Otter from TTCI (AAR) identified this as a research topic for HH Bridges. As presented in the 15th Annual Research Review in Pueblo, Colorado (Otter and Joy, 2010), there is a satisfactory performance up to date in the beams already installed under 149 Millions of Gross Tons (MGT) (135 million gross metric tons) HAL.

This same presentation by Otter and Joy pointed out that the deck inspections at 20 and 95 MGT (18 and 86 millions of gross metric tons) showed improved performance. In their conclusions, Otter and Joy pointed out the benefits of using this new material for the railroad industry. Otter and Joy grouped these benefits in both short and long term objectives. They concluded in their paper that studies in new materials for railroad bridges have a promising perspective.

Finally, John Hilman has recently been recognized with the ENR 2010 Award of Excellence. This recognition was documented by the Structural Engineering Association of Illinois (SEAOI) (2010) and pointed out as an engineering achievement for the North American structural engineering industry. The ENR provided Hilman with this national

recognition in engineering for being the creator of the HCB. As this publication pointed out (SEAOI, 2010) there are three bridges already built using HCBs.

The concept design of the HCB is shown in Figure 6.2, along with the installation of one HCB in the TTCI (AAR) for railroad traffic testing.



Figure 6.2. HC Bridge Company diagram (L) and product (R) while erected in Pueblo, Colorado (courtesy of HC Bridge Company, LLC).

6.3 Load and Resistance Factor Design (LRFD) adaptation for the design of railroad bridges

During the course of this survey-based study, some bridge engineers working for the railroads showed interest in research studying the adaptation to railroads of the LRFD approach. LRFD is currently followed by the American Association of State Highway and Transportation Officials (AASHTO, 2009) and other bridge administrations. This design approach is used to design bridges and bridge elements by controlling their failure probability to an acceptable value. LRFD could replace the allowable stress design (ASD) approach currently presented in the MRE (AREMA, 2009).

The motivations behind investigating an adaptation of AREMA to LRFD are two-fold:

1. Railroad and highway bridges could be better compared if they have been designed under the same philosophy (according to structural engineers working for the railroad)
2. Design practices could benefit from adopting an LRFD approach for railroad bridge design practice, furthering joint development thereafter between highways and railroads

However, some engineers working for railroad, consulting, and construction firms thought it would be difficult to introduce this change in the AREMA code. In their opinion, there are still significant issues to be overcome when adapting LRFD's theoretical basis to actual designs.

To date, the usual solution has been to select combinations of load and resistance factors that produce comparable structures to those designed to recent ASD codes. The uncertainty of both the loads and the structural capacities should be explored from a very large quantity of data on both loads and structural properties to produce an improved

design, and that would involve a tremendous amount of work with a very low improvement in LRFD factors.

Experienced railroad bridge structural engineers showed a mixed interest in these studies. Overall, they do not think that the way railroad bridges are designed today would be modified by an adaptation to the LRFD design methods in the short term. The only reason to develop an LRFD specification for railway bridges to replace, or use as an alternative to, the existing specification would be if it produced comparable designs with significantly less effort.

Figure 6.3 shows a typical short span bridge design under the current ASD philosophy presented in AREMA.

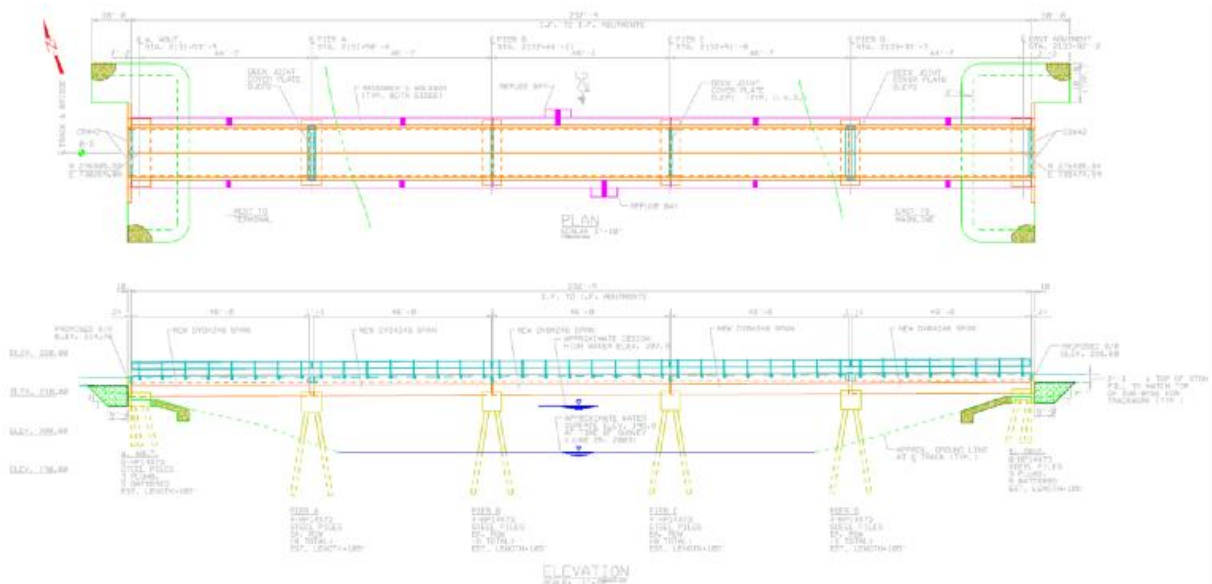


Figure 6.3. Typical brand new railroad bridge with short prestressed prefabricated spans supported by H-piles driven into ground.

6.4 New steel bridge standards development

Consulting structural engineers dedicated to the design of new bridges for the railroads expressed interest in research generating standard bridge sections for steel railroad bridges. According to this group of structural engineers with experience in railroad bridges, currently there are prestressed standards in the railroad industry for Double Voided Beams (DVB) and other precast elements (Figure 6.4). According to the interviewees, these drawings are already generated for certain span lengths. Thus, Class I railroads have predefined span lengths that are already calculated and will be placed in their bridge designs. According to some railroad bridge structural engineers, there would be an interest in producing standard sections for the steel beams so they could also be pre-designed (Figure 6.5 shows a typical steel Through Plate Girder, TPG). They concluded that these standard steel sections could be used during the design phase in the same fashion as the prestressed beams (ballast slabs, DVB, and other precast elements) are used today.

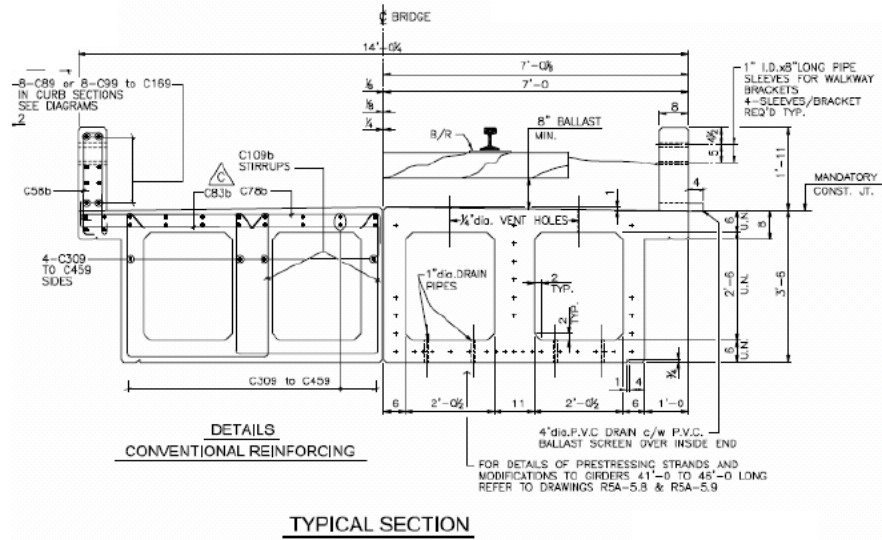


Figure 6.4. Typical PC section used in railroad bridges.

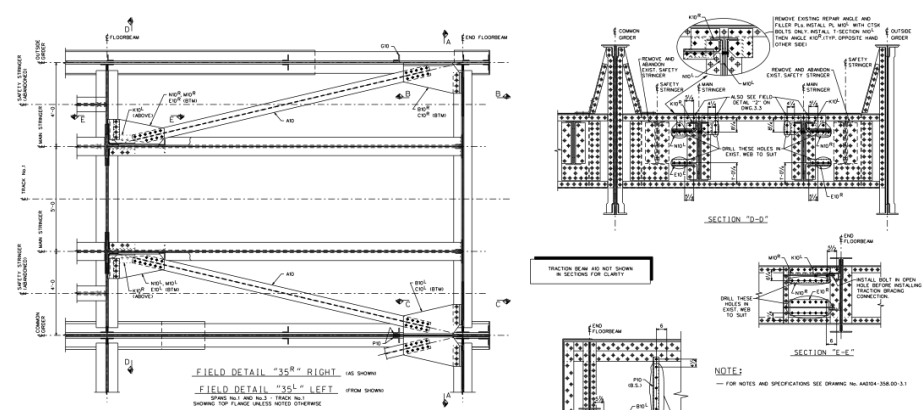


Figure 6.5. Steel TPG details.

6.5 Finding railroad bridge damage (local damage detection)

During the course of this survey-based study, some railroad bridge structural engineers working for the railroad (from the Class I railroads and from the short and medium railroads) expressed interest in studies that could help identifying and locating bridge damage. Figure 6.6 shows inspections of damaged bridges by railroad personal and contractors. The following describes specific interest coming from specific sectors within the railroads:

1. Class I bridge structural engineers working for the railroad would be interested in research methods that could detect damage location in bridges through specific instrumentation or inspection methodology. Ground Penetration Radar (GPR) applications to structural members were proposed or suggested. Structural engineers in charge of bridge management would support research toward methods that could identify the structural capacity of railroad bridges and additionally locate deficient members/elements.

2. Short and medium railroad bridge structural engineers asked for research investigating a substitution to timber boring methods. Timber boring is employed today for damage detection and bridge inspection. This method assesses the actual section of timber bridges through an exhaustive boring program executed element by element. Experienced bridge inspectors also advocated for developing methods that would determine and quantify bridge damage. In their opinion, current technology could improve inspection and bridge assessment by:
 - a. Reducing inspection time
 - b. Improving the quality of the inspection
 - c. Reducing inspection costs to the railroads



Figure 6.6. Railroad bridge inspection looking for local damage.

Finally, past studies following the 1987 NSF Workshop carried out by the AAR in the nineties (AAR, 1993) explored the NDE of civil engineering structures. More recently, Duane Otter pointed out that NDE Techniques are a future trend in the research and development of HH Bridges (IHHA, 2009) for the “assessment of existing railroad bridges.” In this same publication, Otter states that “future developments might be able to help locate new (bridge) defects.” Finally, NDE techniques are already being researched for different applications and the ongoing efforts would reduce costs to railroad researchers. For example, according to Washington (2009), the University of South Carolina received \$4M to detect bridge damage by the use of specialized sensors. On the other hand, other university studies and private initiatives include studies by Rus et al. (2006) and Nyborg et al. (2006).

6.6 Fatigue in railroad bridges: current topics

In 1997, Tobias and Foutch pointed out that it has been precisely recently when the steel bridges built up to over a hundred years ago need to be looked and monitored to prevent that the accumulation of loads over time does not translate into fatigue failures or deficiencies. Studies and research projects dealing with fatigue could range from real case studies to modeling and analysis (Byers et al., 1997; Byers, 2006).

Numerous studies have been performed recently by Class I railroads in the field. These studies monitored and identified stresses and strains under the railroad traffic, and their effect in the integrity of the bridge members under traffic (Uppal and Fry, 2000; Akhtar and Otter, 2008). According to Unsworth (2003), HAL changes in the last decades increase the number of fatigue cycles in railroad bridges.

In 2009, Sweeney defined fatigue in the *Guidelines to Best Practices for Heavy Haul Railway Operations. Infrastructure Construction and Maintenance Issues* (IHHA, 2009) as: “the process of initiation and growth of cracks under the action of repetitive load. As the crack grows, a point is reached where rapid brittle fracture will occur, resulting in failure of the material at that point.” As brought up by AAR officers in charge of research projects in railroad bridges, there is a big demand today in assessing the fatigue capacity and performance of steel bridges under railroad traffic. This survey-based study has identified fatigue a significant concern for structural engineers in charge of steel railroad bridges. Otter and Joy (2010) presented in the 15th Annual Research Review recently fatigue as a research priority today in railroad bridges.

There has been considerable emphasis toward determining the remaining fatigue life of railroad bridges. In addition to the practical value of good predictions, the fast and powerful development of computational mechanics to model the response under loading histories of existing bridges has contributed to this interest. However, the large amount of variation observed in laboratory fatigue tests makes total fatigue life predictions for individual railroad bridges highly uncertain. Therefore, the value of modeling past fatigue exposure diminishes significantly.

The most practical approach related to fatigue is likely to be repair, as needed, until the frequency and cost of repairs to a bridge becomes excessive. The use of remaining life models could be handy in long-range budgeting for renewal of a relatively large group of similar bridges (for example: DPGs, TPGs) or for screening removed spans for possible reuse.

Figure 6.7 shows a steel railroad bridge with over a hundred years old steel members under used today.

6.7 Seismic studies and topics related to railroad bridges in U.S.

In 2009, Bill Byers stated that “railway bridges have been destroyed in earthquakes” and that “earthquakes bridge damage may have the greatest impact on railroad operation” (IHHA, 2009). According to Byers, typically people overestimate the railroad bridge capacity to withstand earthquakes, and further research should be carried out to protect railroad bridges and networks properly. According to Byers, earthquake damage to railroad bridges is likely to take the longest time to repair.

However, it is also true that although earthquake damage to railroad bridges receives significant attention by earthquake engineers, other damage to the railroad network may be more disruptive to railroad operations after the earthquake (Byers, 2004). Byers’ research further identified the extent of earthquake damage in railroad bridges caused by the following:

1. Construction details
2. Local ground conditions



Figure 6.7. Class I railroad bridge with a main truss span and two plate through approaching spans.

3. Magnitude of the earthquake
4. Distance of the bridge to the fault of rupture

Although a sizeable number of railroad bridges have been damaged in earthquakes, they represent only a portion of railroad earthquake damage. According to Bill Byers, of 113 earthquakes identified as damaging railroads, 58 are known to have damaged bridges. In two of these, the bridge damage was caused by tsunamis; in 11 of the 58, bridge damage was the most serious damage reported. Seven of the remaining 55 earthquakes are known to have caused no bridge damage, and in three of these (with magnitudes of 7.5 to 8.4), the other railroad damage was severe to extreme. No bridge damage was reported in the remaining 48 earthquakes, but it is reasonable to assume that at least a few of these earthquakes caused some bridge damage, probably minor, that was not reported. In North America, railroad bridges have typically sustained significantly less earthquake damage than highway bridges. This is probably related to both typical details and the much larger horizontal design loads typically used for railroad bridges (Byers, private conversation, 2011).

It is generally accepted by the structural engineering experts today that the performance of structural elements under seismic excitation has been of paramount focus in the structural engineering community, especially after the notable earthquakes of 1971 at San Fernando, California, and other significant ones as Northridge, California (1994) and Kobe, Japan (1995) (Lee et al., 2005). However, these studies have been focused mostly to highways and building structures. The main reason that research directed to the specific performance of railroad bridges under earthquakes may be related because little damage has been found in railroads following earthquakes (Anonymous, 1994a).

The MRE Chapter 9 lists the requirements and details involving design requirements for railroad bridges under seismic forces, which were introduced in practice in 1994 (AREMA, 2009). Many railroads have established policies for operations after earthquake events, according to this same publication. Luo compiled studies from the Japan experience in safety assessing trains in seismic events (Luo, 2004).

Some railroad bridge structural engineers pointed out during the course of this survey-based study that current monitoring equipment and sensors could help railroad bridge engineers to detect and compare accelerations originated by trains versus those originated by earthquake, thereby determining the severity of the shake as compared to daily performance of the bridge under trains. According to Kavars, this was the case in a monitored bridge over the Mississippi river. Kavars explained that acceleration records helped bridge officials to neglect the effect of a recent earthquake into the main structure, since the bridge responses under the seismic event were much smaller than those measured under regular traffic (Kavars, private conversation, 2010).

Finally, recent studies by Kavars showed that dynamic monitoring of structures could assist in the evaluation of their performance under dynamic loading (Kavars, 2010). Maragakis already identified a decade ago that current technology and future development of dynamic tools for bridge assessment and monitoring could assist to both designing and maintaining railroad bridges against seismic forces (2001).

Research efforts directed in the dynamic monitoring of railroad bridges would help railroads to have a safer and more reliable network, (Tsai and Lee, 2005). Figure 6.8 shows the SHM program deployed over the Mississippi river for identifying bridge response during adjacent construction. Figure 6.9 shows dynamic records measured under an earthquake excitation, in yellow.

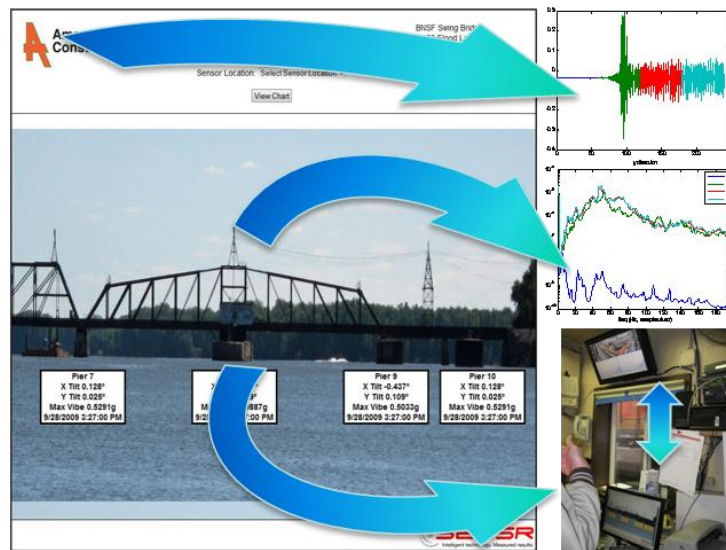


Figure 6.8. Dynamic monitoring under trains over the Mississippi river.

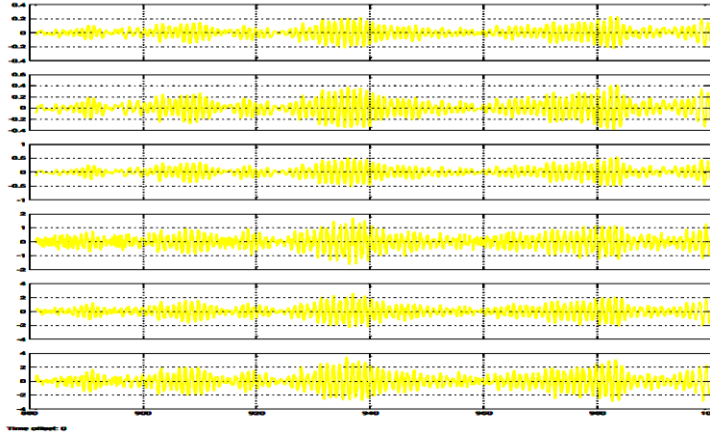


Figure 6.9. Dynamic records measured under earthquake excitation (simulation).

SURVEY RESULTS

7.1 Survey summary and results collection

This report has briefly the current research topics of interest by the railroad bridges and structural engineering industry in North America. Chapter 1 has presented a general description of North American railroads and, specifically, North American railroad bridges. Chapter 2 described the survey methodology, the population interviewed, and the different questions and topics covered. In Chapters 3, 4, 5, and 6, this survey-based study presented the compilation of potential research topics according to the population described in Chapter 2. Chapter 7 presents the results of the ranking of the responses collected during the survey, in order to prioritize research efforts toward current interests and needs from the railroad bridge structural engineering community.

Table 7.1 summarizes the compilation of the answers and discussions collected during the survey-based study about current research topics on Railroad bridges and structural engineering. The column on the left under the label “Topic” presents the main topics covered during the survey. These six topics were selected based in the amount of interest presented during the interviews by the entire population consulted.

The responses have been categorized in six different categories: in favor, not in favor, not applicable (NA), total, weighted, ranked. The method followed to fill each of the categories for each of the research topic is explained below.

1. In favor: the number in this column represents the partial percentage of the responses that showed interest in that particular topic. This percentage is based in the ratio of the number of interviewees covering the topic questioned over the total number of interviewees.
2. Not in favor: percentage of the answers that showed either a clear opposition or a somehow negative disposition to conduct attention and efforts toward that specific topic listed.
3. NA: percentage of the responses that did not have a strong disposition towards that research topic.
4. Total: total number of interviews that actually covered that specific topic in their responses. Not all of the interviews covered the six research topics listed on the left since in occasions the research topics were presented at some point in the middle of the survey-based study.
5. Weighted: this column ponders the percentage of the favorable responses over the number of responses. The values shown in the first column are weighted by the significance of the number of responses to the total.
6. Ranked: the relative importance position (from 1 to 6) is assigned to each research topic based on the weighted answers calculated in column 5.

The results of the survey are listed in Table 7.1. This survey-based study has compared the results of this survey-based study to those of the 1987 NSF Workshop (based on the paper by Byers and Otter from 2006 collecting the results, and the priorities identified at that time).

Table 7.1. Survey results summary and ranking.

2010-11 TOPIC	RESPONSES					
	In favor, %	Not in favor, %	NA, %	Total	Weighted	Ranked
Long Span Bridges	100	0	0	9	13	3
Approaches	100	0	0	9	13	4
Deflection Measurements	86	7	7	14	17	1
High Speed Trains	79	21	0	14	16	2
New Design Loads	62	38	0	8	7	6
Longitudinal Force	31	57	12	16	7	5

The motivation for this comparison between the two studies is threefold:

1. To link the study carried out today with that of 1987 in order to legitimate the interest and context of this survey
2. To validate the topics and results obtained in this survey by comparing the concepts covered in the past
3. To promote further studies of this type in order to show the importance of surveys for identifying and dealing with research topics exploration and knowledge

That comparison clearly illustrates the evolution of terminologies and topics between 1987 and 2010-11, further validating the need for this new survey-based study. This side-by-side comparison acknowledges that there are some similarities between research areas from over 20 years ago and today. For example, both studies identify successfully and economically making various types of railroad bridges field measurements as a high research priority. Table 7.2 presents the results of this comparison.

Table 7.2. Comparison of research topics between 2010-11 and 1987.

2010-11 TOPICS	2010-11 RANKING	1987 TOPICS	1987 RANKING
Deflection measurements	1	Field stress measurements	1
High speed trains	2	Investigate impact factor and effects	2
Long-span bridges	3	Fatigue life	3
Approaches	4	Determine longitudinal forces	4
Longitudinal forces	5	Develop better analysis for design	5
New design loads	6	Timber non-destructive testing	6

7.2 Survey main findings and conclusions

The current survey has identified the need to approach the bridge design, construction and management from a strictly economic point of view as the most important particularity governing structural engineering in railroad bridges. The chief governing need for engineers is to assure the structural integrity of their railroad bridges in use and to communicate their actual structural capacity within personnel and departments within the railroads. Decisions regarding railroad bridges and structural engineering in design, management, maintenance, and construction should always be made to reinforce the safety of railroad operations.

Railroads bridges and structures departments must maximize their resources and investments in this direction, involving:

- (i) Personnel
- (ii) Materials
- (iii) Capital

Designing, building, and maintaining railroad bridges must be directed from an economic view, to ensure the safety of railroad operations.

In these lines, the findings have been grouped in four different categories identifying research interests from a managerial point of view. Each category includes potential research topics in railroad bridges and structural engineering related to that specific level. Each category lists potential research areas as identified by this survey-based study that could assist railroad bridge structural engineers to economically ensure safer bridges at that particular stage of bridge management. The four categories are: bridge design, structural assessment, structural maintenance, and future challenges.

The potential research topics assigned to each category are listed below.

- a. Designing challenges:
 - i. Developing steel standards
 - ii. Modifying E80 Cooper load
 - iii. Adapting LRFD to railroad bridges
 - iv. Review of both LF and IF
 - v. New designs for bridge approaches
- b. Determining and quantifying the following for existing bridges:
 - i. Robustness of bridges and of their foundations (scouring)
 - ii. Use of data collection
 - iii. Rating methods
 - iv. Bridge inspections
 - v. Damage detection
 - vi. Timber trestle assessment
- c. Maintaining existing bridges:
 - i. Extending life of bridges
 - ii. Prioritization of member replacement for railroad bridges
 - iii. Rapid bridge replacement: current practices and techniques
 - iv. Fatigue measurements and remedies
 - v. IF attenuation
 - vi. Bridge approaches maintenance
- d. Foreseeing and planning future challenges in railroad bridges:

- i. High speed railroad bridges (upgrade and design)
- ii. Possibility of increasing load/car in the future
- iii. Performance and recovery after seismic catastrophic effect
- iv. Long span bridge replacement for bridges over 100 years old
- v. Economic approach to railroad bridge replacements
- vi. New materials for railroad bridges

CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions: current research topics in railroad bridges and structural engineering

A survey of sixteen structural engineers has been conducted. The combined experience of the sixteen interviewees in railroad bridges and structural engineering added up to more than 500 years. The goal of the survey was to identify the main structural engineering topics for railroad bridges today. Consultants, contractors, federal officers, and railroads were interviewed during the course the survey. Both experienced engineers and entry-level personnel were questioned about their opinions regarding several research topics involving railroad bridges and structural engineering. The interviewees were given the opportunity to propose additional different research topics based on their own experiences and opinions, and those were also listed and collected for consideration.

As a result, this survey-based study proposes a list of current research topics in railroad bridges / structural engineering. The importance of the topics listed has also been tabulated, based on the number of mentions and the interest shown by the different structural engineers interviewed. Parallel to the interview process, related literature and selected readings were collected, these have also been listed in the reference section of this study. Additional experts on multidisciplinary areas were consulted, and their inputs have also been included in this report at different levels.

The railroad industry in North America is a private investment that needs to make a profit by maximizing resources and limiting costs. Railroad bridges are a cost to railroads, and so the main role of structural engineers in charge of railroad bridges is to use the available resources to maintain a safe network under a limited budget. According to this survey-based study, determining the capacity of bridges that are in service has been identified as the top responsibility and concern of the engineers in charge of railroad bridges – assessing the performance of railroad bridges in the field under real railroad traffic to allow more objective decision making. Investing in maintenance tools that can assist in improving bridge capacities once they have been assessed has also been identified. Quick replacements and member prioritization are of interest, too, so research of new materials and construction methods are valued. Finally, the design of alternatives for future demands like HSR and HAL, and the need to replace bridges that are over 100 years old, are other priorities for railroad bridge structural engineers today.

The promising future of freight and passenger railroad traffic in the United States needs to be seconded by an upgrade in the railroad infrastructure supporting it. This improvement and development of the railroad infrastructure will need to address in particular the most complex elements of the railroad infrastructure, their bridges. A growing railroad industry needs to be supported by healthy and robust bridges. Economic and safety considerations are both concerns of the railroad industry in the United States. A robust, reliable network is safer, more efficient, and therefore more productive.

An overall thrust of general interest was to approach bridge design, construction, maintenance, and management from an economic point of view. According to this study, and in light of new federal regulations for railroad bridge management published by the FRA (2010), future research could be directed toward better enabling the assessment of bridge capacity. A major responsibility and concern of bridge engineers in charge of railroad bridges in North America today is assessing the structural performance, response, and/or decay of those bridges under both: (a) regular loading conditions (long term assessment), and (b) unusual and/or unexpected events (collision, severe scouring, etc.).

This survey-based study ranked measuring deflections under live loads as the current top research interest. According to the majority of the engineers in the survey, measuring real-time deflections under live loading can be beneficial both in terms of railroad bridge management and railroad bridge replacement prioritization, especially for timber bridges. With measurements of accurate bridge performance-related parameters, such as displacement, railroads could direct their annual budgets to only replacing those bridges most in need.

This survey-based study found the potential impact of high-speed trains on current and future railroad bridges to also be of high priority. Interviewees identified this topic as one of growing interest due to the foreseeable need for this research in order to properly accommodate high speed traffic in North America. In their opinion, certain existing bridges would have to be upgraded or completely replaced in order to accommodate passenger trains with higher speeds. This study gave some priority to advancing the knowledge about long-span railroad bridge design, based primarily on the forecasted need of replacing existing longer-span bridges at major elevated crossings that were designed and constructed more than 100 years ago (which sometimes now have significant maintenance costs). Bridge engineers further expressed interest toward research about the maintenance of existing deteriorating bridge approaches, as well as techniques and methods to design more durable railroad bridge approaches in the future. And finally, this survey-based study of engineers placed the examination of longitudinal loads in railroad bridges (their magnitude and distribution, including design implications), as well as the general need for research that develops better design loads and methods for new railroad bridge design, as two other quite important research needs.

Other research topics identified during the survey and parallel literature review were suggested by the railroad bridge structural engineers as areas of some interest for further consideration. Railroad bridge structural engineers generally prioritized investing in whatever maintenance tools could assist them in measuring and/or improving bridge capacities. This group of experts identified the need for developing new methods of measuring bridge foundation robustness during and after scouring events. Additionally, quick bridge replacements and member replacement prioritization are of emerging interest, as are research on new materials and construction methods.

In conclusion, this independent study has identified the structural assessment of railroad bridges as the main structural engineering research topic today. The next section describes suggested steps to be taken in the future to further develop this current need of the railroad bridge engineering community, as well as general recommendations involving future research for railroad bridges.

8.2 Future research steps and recommendations: Structural Health Monitoring (SHM) and railroad bridges in the U.S.

Efforts towards railroad bridge structural engineering field assessment have been recognized as a main interest of structural engineers to improve inspection and maintenance operations. Bridge assessment and monitoring will also benefit and improve new bridge construction control, as well as bridge replacement prioritization. Research must be directed to areas that can assist toward prioritizing railroad bridge replacements, and to implement intelligent and efficient decision-making tools in the railroad bridge industry. Objective data collection in the field can help quantify bridge structural capacity and provide a structural engineer with ways of more efficiently determining which bridges and/or bridge elements to replace under a limited budget. Determining the capacity of existing timber trestles (still in significant use in the United States today) can benefit from this. Construction activities can also be improved from data collection, in order to protect existing structures from adjacent construction operations. New means and methods, technology, and materials will assist in quick bridge replacements. The railroad engineering community should promote interdisciplinary collaborations between different engineering areas to incorporate new technologies that can assist and develop inexpensive tools that are easy to install and read, such as wireless sensors. The recent proliferation and development of these new data collection sensors (wireless sensors for SHM) in the last 10 years, along with pilot experiences presented in this study, identify this as an area that should be researched in the near future by railroad bridge structural engineering institutions and affiliated laboratories. This is, incidentally, quite similar to something recently called for as a particular area for research and development in the AREMA President's column (Unsworth, 2011).

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APPENDIX A: INTERVIEWEES BRIEF BIOS

The following 16 engineers were the main input used during the survey. A short biography describes their current and past experience with railroad bridges and other related structural engineering exposure. Their time is greatly acknowledged.

Barrett, John, PE, SE, is the Vice Chairman of Bowman and Barrett Associates, an Engineering Consulting based out of Chicago which he cofounded. Mr. Barrett has 60 years of experience in the design of railroad bridges, and has led hundreds of projects to become one of the nation's foremost experts on railroad bridge design. Mr. Barrett's affiliations include: AREMA Committees 9 (Seismic) and 15 (Steel), being the past Chairman, member emeritus and life member of the later; American Institute of Steel Construction (AISC), ASCE, American Society for Testing and Materials (ASTM), American Welding Society (AWS), National Society of Professional Engineers (NSPE) and SEAIOI. Recently, SEAIOI recognized him with the John Palmers award (June 2010). Mr. Barrett is a licensed SE in Illinois and a registered PE in 16 states.

Byers, William G., PE, has more than fifty years of experience in railway engineering, primarily bridge engineering, and is a nationwide expert in seismic design and performance of railroad bridges. Mr. Byers was in charge of the Santa Fe Railway's bridge design office and field forces before their merger to BNSF. Mr. Byers has provided international earthquake damage inspection and also assisted in developing earthquake response policies. Mr. Byers has chaired the AAR Bridge Research Advisory Group and AREMA Committee 9 (seismic) in which he is a member emeritus. Mr. Byers also was a member and past chairman of the American Railroad Engineering Association (AREA) Committee 16 and is a member emeritus of AREMA Committee 15. Mr. Byers is a licensed PE in seven states.

Carter, Jim is Chief Engineer Bridges & Structures for NS, headquartered in Atlanta. His duties include responsibility for setting policy for the management of bridges, tunnels, and culverts, and overall responsibility the Structural Capital Improvement Program, and repair program. He joined Norfolk and Western Railway as a Management Trainee in 1975 after receiving his Bachelors of Science in Civil Engineering (BSCE) from Virginia Tech, where he was also a Co-op student with Southern Railway. He has since served in various NS field and office positions. Mr. Carter is the current President of AREMA; a member of AREMA Committee 15 – Steel Structures; a member of the ASCE, and the Coasts, Oceans, Ports, and Rivers Institute; a member of the Alumni Advisory Board of the Via Department of Civil and Environmental Engineering Department at Virginia Tech. Mr. Carter is a registered PE.

Eschenbach, John, Class a registered general engineering contractor in California, is a senior project manager for Amtrak. Mr. Eschenbach has more than 34 years of experience under Amtrak, and has worked in the positions of bridge foreman, bridge inspector, bridge supervisor, resident engineer, project director, senior project director and senior project manager. He is an active member of AREMA Committee 11. Mr. Eschenbach has managed numerous construction projects on Amtrak's North East Corridor and Amtrak West, such as grade separations, construction of equipment and

maintenance facilities, stations, platforms, track reconfiguration projects, bridges and railroad capacity infrastructure double track projects.

Franz, David, PE, is Regional Bridge Engineer of Osmose Railroad Services, Inc.. Mr. Franz has more than thirty years of experience working for railroads, consulting and construction companies. Mr. Franz started his railroad career in 1976 with the Milwaukee Road in Chicago as a bridge inspector. In 1989, Mr. Franz became the bridge engineer for Kansas City Southern. In 1999 Mr. Franz started working for Osmose Railroad Services as regional bridge engineer. Mr. Franz has been active in the old American Railway Bridge & Building Association and AREMA, and has served on both boards as a director and vice president. Mr. Franz is a member of AREMA Committee 8 Concrete Structures and Committee 10 Structures Maintenance & Construction, where he was past chairman and actively involved in the development of the Bridge Inspection Handbook. David is a registered PE in Wisconsin and Kansas.

Herbeck, Jeff, EIT, is a Supervisor Structures in Saint Louis, MO, for BNSF. Mr. Herbeck finished his Bachelors in railroad engineering at the Railroad Engineering Program in the CEE Department at the UIUC in 2005. Following graduation, Mr. Herbeck worked for the Canadian National Railway for three years, ranging positions from bridge inspector to track supervisor in Wisconsin, Louisiana and Michigan. In 2008, he started working for BNSF at their main office in Chicago, Illinois. Mr. Herbeck experienced is related to bridge design, construction, replacement, and maintenance operations. Mr. Herbeck is a member of AREMA.

Kleinhans, Danielle, PhD, PE is a Senior Engineer and Group Manager of Structural Engineering and Mechanics, as well as Chair of the Transportation Industry Practice Group, at CTLGroup. Dr. Kleinhans has more than eight years of experience in the design, construction, maintenance and monitoring of bridges, both highway and railroad bridges. Dr. Kleinhans is an expert in the use of fiber reinforced polymers for bridge construction. Prior to her job at CTLGroup, Dr. Kleinhans was a bridge design engineer at Modjeski and Masters, Inc. Dr. Kleinhans was one of the lead engineers for the monitoring of the Huey P. Long Bridge widening (2009-2013), the longest railroad bridge in North America, with more than an eight hundred sensors installed.

Le, Hoat, Masters in Engineering (MEng), PE (California), System Engineer - Bridge Assessment, CN. Mr. Le is in charge of CN's Headquarters Bridge Assessment group, which is located in Homewood, Illinois. His group is responsible for determining and documenting the load carrying capacity of CN's bridge inventory, using analytical methods supplemented with load testing results. Other functions of the group includes making recommendations on the maintenance, rehabilitation and replacement of CN's bridges, providing technical support during emergencies involving bridges, approving special dimensional loads operation over CN's bridges, and endorsing the purchase and/or operation of locomotives and rolling equipment. Mr. Le has over thirty two years of experience in the analysis, rating and load testing of steel, concrete and timber bridges.

Lozano, Don is retired Assistant Director of Structure for BNSF at Kansas City, Kansas. Mr. Lozano has worked 41 years in various positions with Atchison, Topeka and Santa Fe (ATSF) Railway and BNSF involving the design, construction, maintenance and

inspection of railroad bridges. Mr. Lozano specialized in remediation of unusual structural problems in railroad bridges. These projects include diagnostics and repair of compromised pier foundations due to streambed scour. In 2008, Mr. Lozano initiated the use of electronic instrumentation on BNSF to supplement routine visual bridge inspection methods. The electronic data is used to diagnose pier reactions to live loads that are otherwise undetectable by visual inspection methods. The electronic data is also used to establish the history of pier reactions to live loads. Mr. Lozano belongs to AREMA Committees 1 and 10. He is currently working as the Vice President-Structures for J.L. Patterson & Associates in Orange County, CA.

Manzanarez, Rafael, PE, Professional Engineer (PEng), is the Vice President and Project Manager at T.Y. Lin International in San Francisco, CA. Mr. Manzanarez has more than 30 years of experience in bridge design, construction and retrofit, both highways and railroads. Mr. Manzanarez is an expert in long span bridges, seismic design, suspension cable and cable-stayed bridges. In addition to his experience in the design and construction of long span bridges, Mr. Manzanarez has published numerous articles in peer reviewed publications and given several lectures in this topic across the world. Mr. Manzanarez's memberships include the American Segmental Bridge Institute (ABSI) and the International Association of Bridge and Structural Engineering (IABSE).

Otter, Duane, PhD, PE, is a senior engineer at the TTCI, a subsidiary of the AAR in Pueblo, Colorado. Dr. Otter works as the leader of the bridge research team. Dr. Otter obtained his bachelor's degree from Calvin College, and his PhD in Civil Engineering at the University of Michigan at Ann-Arbor. Dr. Otter has been a member of the AAR and TTCI since 1989. Dr. Otter is active in AREMA Committees 8 (Concrete Bridges and Foundations), 9 (Seismic Design) and 15 (Steel Bridges). Dr. Otter is also a member of the TRB Committee on Dynamics and Field Testing of Bridges. Dr. Otter is a registered PE in the state of Colorado.

Payne, Richard D., PE, SE, has been the President of ESCA Consultants, Inc. (ESCA) since 1989. Mr. Payne has been working on railroad projects since 1969. Mr. Payne activities with railroad projects have ranged from design, construction and inspection to structural assessment, repair, retrofitting and replacement. Mr. Payne is a member of ACI (American Concrete Institute), SEAOL, and AREMA (Committee 8). Mr. Payne chaired AREMA Committee 8 from 2003-2006. Mr. Payne is a licensed SE in 9 states.

Riehl, Bill, PE, is the President of Americanrail, the largest small and medium railroad carrier in North America, with more than 3000 miles of track. Mr. Riehl has more than 30 years of experience in the construction, inspection and maintenance of railroad bridges, with an emphasis on timber trestles. Mr. Riehl has been working for Americanrail for over twenty years. Prior to that Mr. Riehl had both inspection and construction positions in short and medium railroads. Mr. Riehl is an active member of AREMA Committees 7 and 23. Mr. Riehl is a licensed PE in 3 states.

Scola, Sandro, MEng, PEng is the Senior Manager Structures for the CN in the United States. Mr. Scola has been working in the railroad industry for more than 20 years. Mr. Scola has been involved in design, construction, maintenance, inspection and upgrading of all types of railroad bridges and structures. Mr. Scola served as an adjunct professor in

Civil Engineering at McGill University (Montreal, Canada) and continues to assist in their Survey School. Mr. Scola is an active member of AREMA Committee 7 and Canadian Standards Association (CSA) W59 Committee. Mr. Scola is a registered PEng in both Quebec and Ontario. Mr. Scola works in Homewood, Illinois, at the CN Headquarters in the United States.

Sweeney, Robert A. P., PhD, Doctor in Engineering (DEng), PEng works for Modjeski & Masters Consultants. Dr. Sweeney assists with bridge evaluations, inspections, remaining life predictions and bridge management. Dr. Sweeney has worked 37 years for the CN, where he was the Head of Structures. Dr. Sweeney is a Fellow of the IABSE, Canadian Society of Civil Engineers (CSCE) and ASCE. Dr. Sweeney is also a Member Emeritus of the TRB-Dynamic & Bridge Testing, AREMA Committee 15, and the AAR Bridge Research Advisory Group. Dr. Sweeney is a licensed PEng in 3 Canadian Provinces. Dr. Sweeney has personally visited and inspected nearly 9,000 bridges during his career.

Unsworth, John F., PEng, MEng is the Manager, Structures Planning and Design at CP. Mr. Unsworth has been working in the design, construction, management and maintenance of railroad bridges over 25 years. Mr. Unsworth is a former President of AREMA (2010-11), and has also served as the Chair of Committee 15 (Steel Structures). Mr. Unsworth is the Chair of the AAR Bridge Research Advisory Group, and a registered member of the IABSE, CSCE, and TRB Steel Bridges Committees. He has authored numerous technical publications and book chapters, and the book “*Design of Modern Steel Railway Bridges*” (2010). Mr. Unsworth is a registered PEng in 6 Canadian Provinces.

APPENDIX B: ACKNOWLEDGEMENT OF ADDITIONAL INPUT

The following engineering professionals have also provided valuable inputs in different areas of this independent study. Their time and insights are also acknowledged:

Brode, Steven, President, (W. M. Brode Company, Engineers and Builders)

Cavaco, José, Bridge and Structures Engineer (CN Railways)

Chapa, Sal, PE, Project Engineer (CTL Consultants)

Chin, Robin, Systems Engineer (Rockwell Collins Inc.)

Chiu, John, Graduate Student in Structural Engineering, CEE (UIUC)

Codd, Patrick, Software Engineer (Apple, Inc.)

Dauids, Gordon, PE, Chief Engineer-Structures (retired) (USDOT, FRA)

Day, Kevin, PE, Engineering Manager (CN Railways)

Dooley, Mike, PE, SE, Vice President (ESCA Consultants Inc.)

Dowbor, Peter, Automobile Controls Division Engineer (retired) (Eaton Corporation)

Drapa, Joe, Signaling and Control Railroad Engineer, TTCI (AAR)

Foutch, Doug, PhD, SE, Emeritus Professor in Structural Engineering (UIUC)

Fuggini, Clemente, PhD, Research Engineer (D'Appolonia, Italy)

Gamble, William, PhD, PE, SE, Emeritus Prof. in Structural Engineering (UIUC)

Gioachin, Filippo, PhD, Hewlett Packard Laboratories (Singapore, Singapore)

Guo, Xun, PhD, Professor in Structural Eng. (China Earthquake Administration, China)

Halterman, Arne, PE, SE, Project Manager (Holmes Culley Engineers)

Henkel, Eric, PE, SE, Vice President (ESCA Consultants Inc.)

Hilman, John, SE, PE, CEO (HC Bridges Ltd.); Senior Associate (Teng & Associates)

Iba, Daisuke, PhD, Assoc. Prof. in Mech. Eng. (Kyoto Inst. Of Technology, Japan)

Jin, Bo, PhD, Project Engineer (Institute of Engineering Mechanics, China)

Jung, Shin Ae, PhD, Assistant Prof. in Structural Eng. (University of Connecticut)

Jung, Sungmoon, PhD, Assistant Professor in Structural Eng. (Florida State University)

Kavars, Chris, Chair and CEO (Sensr Company)

Killingbeck, David, PE, Chief Engineer-Structures (USDOT, FRA)

Kim, John, PhD, PE, Project Manager / Supervising Engineer (Parsons Brinckerhoff)

Kuo, Cory, Project Engineer, The Walsh Group

Kurata, Narito, PhD, Senior Research Engineer (Kajima Corporation, Japan)

Kwon, Oh-Sung, PhD, Assistant Professor in Structural Eng. (University of Toronto)

Lenzini, Peter, SE, PE, Emeritus Faculty in Geotechnical Engineering (UIUC)

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**APPENDIX C: FEDERAL RAILROAD
ADMINISTRATION (FRA) SPEED CLASSIFICATION
TABLE**

Operating Speed Limits by Class of Track

(FRA, 2009)

49 CFR 213.9 and 213.307

Sec. 213.9 Classes of track: operating speed limits.

(a) Except as provided in paragraph (b) of this section and Secs. 213.57(b), 213.59(a), 213.113(a), and 213.137(b) and (c), the following maximum allowable operating speeds apply--
[In miles per hour]

Over track that meets all of the requirements prescribed in this part for--	The maximum allowable operating speed for freight trains is--	The maximum allowable operating speed for passenger trains is--
Excepted track.....	10	N/A
Class 1 track.....	10	15
Class 2 track.....	25	30
Class 3 track.....	40	60
Class 4 track.....	60	80
Class 5 track.....	80	90

Sec. 213.307 Class of track: operating speed limits.

(a) Except as provided in paragraph (b) of this section and Secs. 213.329, 213.337(a) and 213.345(c), the following maximum allowable operating speeds apply:

Over track that meets all of the requirements prescribed in this subpart for--	The maximum allowable operating speed for trains is--
Class 6 track.....	110 m.p.h.
Class 7 track.....	125 m.p.h.
Class 8 track.....	160 m.p.h.
Class 9 track.....	200 m.p.h.

APPENDIX D: LIST OF ACRONYMS

The following acronyms appear one or more times in this report. Their meanings have been included here with the intention of assisting the reader who may elect to read only certain sections of the report, and for the general convenience of any readers unfamiliar with some of the topics covered.

A	Class A - General Contractor (California)
AAR	American Association of Railroads
AASHTO	American Association of State Highway and Transportation Officials
ABC	Accelerated Bridge Construction
ACI	American Concrete Institute
AISC	American Institute of Steel Construction
AREA	American Railroad Engineering Association
AREMA	American Railway Engineering and Maintenance of Way Association
ASCE	American Society of Civil Engineers
ASD	Allowable Stress Design
ASTM	American Society for Testing and Materials
ATSF	Atchison, Topeka and Santa Fe (Railway)
AWS	American Welding Society
BEA	Bureau of Economic Analysis
BMS	Bridge Management System
BNSF	Burlington Northern Santa Fe (Railroad) (Class I Railroad)
BSCE	Bachelors of Science in Civil Engineering
BTS	Bureau of Transportation Statistics
CEE	Civil and Environmental Engineering
CFR	Code of Federal Regulations
CN	Canadian National (Railway) (Class I Railroad)
CP	Canadian Pacific (Railway)
CSA	Canadian Standards Association
CSCE	Canadian Society of Civil Engineers
CSX	CSX (Corporation) (Class I Railroad)
DEng	Doctor in Engineering (Canada)

DOT	Department of Transportation
DPG	Deck Plate Girder
DVB	Double Voided Beam
E80	Cooper E80 Railroad Live Load
EIT	Engineer in Training
ENR	<i>Engineering News Record</i>
FAST	Facility for Accelerated Service Testing
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
GAO	Government Accountability Office
GDP	Gross Domestic Product
GPR	Ground Penetrating Radar
HAL	Heavy Axle Load
HC	Hybrid Composite
HCB	Hybrid Composite Beam
HH	Heavy Haul
HSGTC	High Speed Ground Test Center
HSR	High Speed Railroad
ICRR	Illinois Central Railroad
IABMAS	International Association for Bridge Maintenance and Safety
IABSE	International Association for Bridge and Structural Engineering
IDEA	Innovations Deserving Exploratory Analysis
IF	Impact Factor
IFC	Instrumented Freight Cars
IHHA	International Heavy Haul Association
ISR	Intermediate Speed Rail
KCS	Kansas City Southern (Railroad) (Class I Railroad)
KM	Kilometer
KPH	Kilometers per Hour
LEED AP	Leadership in Energy and Environmental Design Accredited Professional
LF	Longitudinal Force

LRFD	Load and Resistance Factor Design
MEng	Masters in Engineering (Canada)
MGT	Millions of Gross Tons
MHSRA	Midwest High Speed Rail Association
MPH	Miles per Hour
MRE	Manual for Railway Engineering
NA	Not Applicable
NCBC	National Concrete Bridge Council
NDE	Non-Destructive Evaluation
NDT	Non-Destructive Testing
NIPA	National Income and Product Accounts
NS	Norfolk Southern Corporation (Class I Railroad)
NSF	National Science Foundation
NSPE	National Society of Professional Engineers
NYC	New York City
PE	Professional Engineer
PEng	Professional Engineer (Canada)
PC	Prestressed Concrete
PPC	Precast-Prestressed Concrete
RBM	Rigid Body Motion
RC	Reinforced Concrete
RITA	Research and Innovative Technology Administration
RR	Railroad
RRF	Railroad Research Foundation
RSAC	Railroad Safety Advisory Committee
RT&S	<i>Railway Track and Structures Magazine</i>
SE	Structural Engineer / Structural Engineering
SEAOI	Structural Engineering Association of Illinois
SHM	Structural Health Monitoring
STB	Surface Transportation Board
TPG	Through Plate Girder

TRB	Transportation Research Board
TRR	<i>Transportation Research Record</i>
TTC	Transportation Test Center
TTCI	Transportation Technology Center, Inc.
UIUC	University of Illinois at Urbana-Champaign
UP	Union Pacific (Railroad) (Class I Railroad)
USDOT	U.S. Department of Transportation

List of Recent NSEL Reports

<i>No.</i>	<i>Authors</i>	<i>Title</i>	<i>Date</i>
016	Reneckis, D. and LaFave, J.M.	Seismic Performance of Anchored Brick Veneer	Aug. 2009
017	Borello, D.J., Denavit, M.D., and Hajjar, J.F.	Behavior of Bolted Steel Slip-critical Connections with Fillers	Aug. 2009
018	Rice, J.A. and Spencer, B.F.	Flexible Smart Sensor Framework for Autonomous Full-scale Structural Health Monitoring	Aug. 2009
019	Sim, S.-H. and Spencer, B.F.	Decentralized Strategies for Monitoring Structures using Wireless Smart Sensor Networks	Nov. 2009
020	Kim, J. and LaFave, J.M.	Joint Shear Behavior of Reinforced Concrete Beam-Column Connections subjected to Seismic Lateral Loading	Nov. 2009
021	Linderman, L.E., Rice, J.A., Barot, S., Spencer, B.F., and Bernhard, J.T.	Characterization of Wireless Smart Sensor Performance	Feb. 2010
022	Miller, T.I. and Spencer, B.F.	Solar Energy Harvesting and Software Enhancements for Autonomous Wireless Smart Sensor Networks	March 2010
023	Denavit, M.D. and Hajjar, J.F.	Nonlinear Seismic Analysis of Circular Concrete-Filled Steel Tube Members and Frames	March 2010
024	Spencer, B.F. and Yun, C.-B. (Eds.)	Wireless Sensor Advances and Applications for Civil Infrastructure Monitoring	June 2010
025	Eatherton, M.R. and Hajjar, J.F.	Large-Scale Cyclic and Hybrid Simulation Testing and Development of a Controlled-Rocking Steel Building System with Replaceable Fuses	Sept. 2010
026	Hall, K., Eatherton, M.R., and Hajjar, J.F.	Nonlinear Behavior of Controlled Rocking Steel-Framed Building Systems with Replaceable Energy Dissipating Fuses	Oct. 2010
027	Yeo, D. and Jones, N.P.	Computational Study on 3-D Aerodynamic Characteristics of Flow around a Yawed, Inclined, Circular Cylinder	Mar. 2011
028	Phillips, B.M. and Spencer, B.F.	Model-Based Servo-Hydraulic Control for Real-Time Hybrid Simulation	June 2011
029	Linderman, L.E., Mechtov, K.A., and Spencer, B.F.	Real-Time Wireless Data Acquisition for Structural Health Monitoring and Control	June 2011
030	Chang, C.-M. and Spencer, B.F.	Multi-axial Active Isolation for Seismic Protection of Buildings	May 2012
031	Phillips, B.M. and Spencer, B.F.	Model-Based Framework for Real-Time Dynamic Structural Performance Evaluation	August 2012
032	Moreu, F. and LaFave, J.M.	Current Research Topics: Railroad Bridges and Structural Engineering	October 2012