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NCHRP SYNTHESIS 327

Cost-Effective Practices for Off-System and Local Interest Bridges

A Synthesis of Highway Practice

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SUBJECT AREAS
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FOREWORD

By Staff
Transportation Research Board

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

Information exists on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

The synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

This report of the Transportation Research Board examines off-system bridge design, construction, maintenance, financing, rehabilitation, and replacement. For this report off-system refers to those bridges typically owned and maintained by local agencies and by state agencies on rural and other low-volume roads. It will be of interest to all state departments of transportation and local agencies with off-system bridges under their jurisdiction. The report focuses on the best procedures that promote safe, efficient, and cost-effective practices for such bridges. Topics covered include the state of existing bridge populations, maintenance, load rating, rehabilitation, strengthening, geometrics, structural design criteria, replacement alternatives, construction practices, and off-system bridge administration, including funding, environmental permitting, and interagency cooperation and partnering.

This synthesis contains information drawn from survey responses from U.S. state departments of transportation and local transportation agencies, a literature search and review, an owner survey, and a survey of bridge product producers.

A panel of experts in the subject area guided the work of organizing and evaluating the collected data and reviewed the final synthesis report. A consultant was engaged to collect and synthesize the information and to write this report. Both the consultant and the members of the oversight panel are acknowledged on the title page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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This study was managed by Jon Williams, Manager, Synthesis Studies, who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in project scope development was provided by Donna Vlasak, Senior Program Officer. Don Tippman was responsible for editing and production. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

Crawford F. Jencks, Manager, National Cooperative Highway Research Program, assisted the NCHRP 20-5 Committee and the Synthesis staff.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

COST-EFFECTIVE PRACTICES FOR OFF-SYSTEM AND LOCAL INTEREST BRIDGES

SUMMARY

The nation's transportation system includes not only the extensive National Highway System but also the local highway systems that provide important links in the transportation network. Bridges are an essential component of these local systems. The primary focus of this synthesis is on local or off-system bridge design, construction, maintenance, financing, rehabilitation, and replacement. The definition of "off-system" can vary from place to place. Off-system bridges in this report will refer to those bridges typically owned and maintained by local agencies (i.e., cities and counties) and by state agencies on rural and other low-volume roads. Information was gathered from several sources, including a project survey, published literature, electronic media, personal contacts, and manufacturers of bridges or bridge-related products. Several current practice areas that need improvement (e.g., design standards, replacement strategies, and maintenance) were also identified.

Several hundred surveys were disseminated electronically to state and local agencies. Twenty states and 70 local agencies responded, with many of the local agency responses from a small group of states. Survey results indicated a general agreement between state and local agencies on a variety of issues.

Survey responses provided some interesting data. The preferred type of bridge for new construction is a concrete box culvert because of its ease of construction, design, and being essentially maintenance free. Bridge decks were identified as requiring the most maintenance. Survey respondents noted that because of legislative restrictions on the work that can be done in-house and staff size limitations, design and construction of off-system bridges are usually completed by consulting engineers and contractors, respectively. Numerous survey responses indicated the need for improved design standards for off-system bridges and the desire for more flexibility in project funding.

Of the hundreds of deficient, deteriorated bridges in this country, a very large number are locally owned or on "other" low-volume roads. Approximately 30% of the National Bridge Inventory bridges are considered structurally deficient or functionally obsolete. Because bridges less than 6.1 m (20 ft) long are not included in the National Bridge Inventory data, it seems reasonable to assume that the percentage of problematic bridges is even higher. Recent helpful changes in the Highway Bridge Replacement and Rehabilitation Program now permit the use of these funds for preventative maintenance activities that extend the useful life of a given bridge.

More appropriate decisions are required in all areas of bridge maintenance, rehabilitation, and replacement. "Data-based" decisions derived from asset/bridge management, as well as construction techniques, maintenance procedures, materials, etc., to promote extended life, are required. New high-performance materials as well as fiber-reinforced polymer products are currently being researched. Several of these materials show promise for use in off-

system bridges because they have excellent durability, require minimal maintenance, and appear to have long life.

One of the more comprehensive reviews in this synthesis is the coverage provided on bridge strengthening and rehabilitation. In addition to the numerous traditional procedures, several articles on the use of fiber-reinforced polymers in the strengthening of various bridge components are reviewed.

Various aspects of bridge replacement structures are also given comprehensive coverage. Numerous options for off-system bridge replacements including pre-engineered bridges are presented. Bridge design aids, design software, and numerous websites, which can be used to expedite the replacement engineering process, are referenced.

Various administrative issues were reviewed in this synthesis. Bridge management systems for off-system bridges are reviewed. Because asset management systems rely on historic cost data, the degree a given agency can use such a system is a function of the availability of such data. Several examples of bridge and asset management concepts for areas with small populations are presented as are some alternate strategies, such as road abandonment or total road closure. Various sources of funding (and potential new funding) for off-system bridges are discussed.

In addition to traditional funding, additional federal programs such as the Surface Transportation Program and the Innovative Bridge Research and Construction Program are discussed. Information on the environmental process and some of the associated requirements are presented. Sufficient information and references are included to provide bridge owners with assistance in these areas.

This synthesis has identified numerous existing deficiencies, and repair, rehabilitation, and strengthening procedures, as well as replacement options that owners of off-system bridges can employ. The suitability and cost-effectiveness of the many options and procedures identified are likely to vary in different regions of the country. This publication can be considered as a “user manual” or “tool box” of information, procedures, and choices for use by owners of off-system bridges in the management of their bridge inventory.

CHAPTER ONE

INTRODUCTION

The need for a safe and efficient transportation system is of paramount importance. Such a system is the backbone of the nation's economy, whether with respect to the extensive system of Interstate highways criss-crossing the nation or the local roads that allow for ready access to communities. Although not necessarily receiving the attention of the larger Interstate system, the extensive system of non-Interstate highways, as well as other state and local roads and the associated bridges, carry significant amounts of traffic and allow for the local transportation of goods and services. Whether allowing for the transportation of raw farm and mineral products to processing plants or for the delivery of finished goods to a distribution center, the nation's non-Interstate highways form an important link in the distribution network.

NEED FOR THE STUDY

The focus of this synthesis is on the best procedures that promote safe, efficient, and cost-effective practices for off-system bridges. The scope of work as defined by the NCHRP Project 20-5 topic panel is as follows:

> There is a nationwide need to encourage counties and cities to improve the overall sufficiency rating of their structure population. A synthesis of the existing practices and processes used to satisfy reasonable operating standards for off-system bridges and approach roadways is needed.
>
> Bridges that are relatively inexpensive to design, build, and maintain, and that are capable of safely carrying oversized equipment, frequent loading by school buses, and infrequent over-loading by heavy commercial trucks are of particular interest. This may result in the replacement, repair, and/or rehabilitation of substandard bridges and thus increase the efficiency and safety to the traveling public.
>
> The synthesis will survey state departments of transportation (DOTs), local agencies, and the literature to document the practices that lead to the most economical, safe, and functional, off-system bridges. These bridges are defined as those under local jurisdiction.
>
> Specific items of interest include, but are not limited to
>
> - Structural design criteria (design loading, deflection, fatigue, and scour),
> - Geometrics (e.g., width, height, and alignment),
> - Bridge railings (e.g., at the appropriate crash test level),
> - Construction practices (e.g., local agency forces vs. contract, delivery of materials, and constructability),
> - Compliance with environmental regulations (e.g., permitting),
> - Teamwork (e.g., local, state, and federal partnering),
> - Initial cost and maintainability,
> - Funding (e.g., resources available to state and local agencies), and
> - Stockpiling of bridge components (e.g., precast/prefabricated elements, recycled and new elements).

Off-system bridges are defined differently by many agencies. The phrase "off-system" can mean bridges not located on the National Highway System (NHS), bridges not located on Federal-Aid Highways, locally owned bridges, and other connotations. For the purposes of this report, the discrepancy between these definitions is not reconciled. Herein, the various practices described for maintenance, rehabilitation, and reconstruction of off-system bridges are intended to apply to the types of bridges typically owned and maintained by local agencies (i.e., cities and counties), and by state agencies on rural and other low-volume roads.

Existing Deficiencies

A statistical analysis of the Year 2000 National Bridge Inventory (NBI) data submitted in accordance with federal reporting requirements was conducted by the National Bridge Inventory Study Foundation (NBISF 2001), an independent organization that characterizes the NBI statistical information. For each state and the District of Columbia a summary of important data was made, which is available in report form. Additionally, the following data are available on the web (www.nationalbridgeinventory.com) for each state and the District of Columbia:

- Number of bridges on file sorted by route type,
- Structurally deficient/functionally obsolete bridges sorted by route type,
- Number of bridges over waterways,
- Number of scour critical bridges,
- Age of structures,
- Number of routes on and under structures,
- Improvement costs,
- Maintenance responsibility,
- Functional classification,
- Posted bridges,
- Material and design types,
- Bridges with safety features not meeting current standards,
- Type of service on and under bridges,
- Bridges with intolerable appraisal ratings,
- Bridges requiring special inspections,
- Deck structure types, and
- Sufficiency ratings.

The findings of the statistical analysis indicated that approximately one-half of the existing bridges are 25 to 50 years old. Nearly 12,000 bridges (approximately 2% of the national total) are in excess of 100 years old. The deterioration of most of the structures less than 50 years old is minor and progresses slowly, but accelerates rapidly after 50 years. Based on these observed deterioration rates, and the prior statement regarding the majority age of the existing bridge population, a serious problem relative to bridge rehabilitation and replacement will be evident for several decades. This issue is magnified when considering the increases in traffic volumes, density, and truck weights. Cost data submitted as part of the NBI process estimate road and bridge improvement costs to be approximately $200 billion.

Concerning bridge safety, the NBI data analysis with respect to geographic features crossed indicated that more than 80% of the nation's bridges are water crossings and in excess of 20,000 of these bridges have been classified as scour critical, with estimated improvement costs of $7.8 billion. Nearly two-thirds of the bridges in the existing inventory have at least one substandard safety feature.

A study was made of the number of bridges with intolerable structural evaluation, deck geometry, or underclearance. A feature is considered intolerable if rated 3 or less on a scale of 0 to 9. More than 97,000 of the bridges in the inventory have intolerable deck geometry, with estimated improvement costs of $50.5 billion. Nearly 60,000 bridges have structural evaluations considered intolerable, with improvement costs of $19.3 billion. An additional 22,000 have inadequate underclearance and projected improvement costs of $21.6 billion. More than 100,000 bridges have Sufficiency Ratings (SRs) of less than 50, and twice that number have SRs of less than 80. The total number of bridges eligible for either structural rehabilitation or replacement funds from the federal government (per SR numbers) is approximately half of the total bridge inventory. Approximately 134,000 bridges are recommended for replacement because of structural and/or functional obsolescence. The estimated improvement costs for these bridges are $66.5 billion.

Management and Funding Problems

Statistics are important because they define the nature of the problem, both its severity and trends in types and number of deficiencies, but they are not solutions. To resolve the problems of deficient off-system bridges, efficient management policies must be enacted. However, there are significant financial constraints that hamper the complete remedy of bridge deficiencies. Additionally, many local agencies still do not have a systematic approach for planning bridge maintenance, rehabilitation, or replacement.

Of the approximately $101 billion spent in 1997 (one of the years for which spending patterns were examined) for all forms of highway construction, 21% of the funds came from federal agencies, with the balance from state and local governments. This is a significant financial obligation. It will be demonstrated that although off-system bridges, as defined by those not on the Federal-Aid Highways, constitute 48.5% of the public road total, off-system roads received only 22% of the capital funds spent on public roads. Considering all functional classifications in 1997, bridge funding was only 14% of the capital expenditures. These issues will be discussed in more detail in chapter two; the difficulties local agencies have in supporting a large bridge population with limited funds will also be discussed.

PROJECT APPROACH

The approach taken toward fulfilling the various objectives for this synthesis had several main focuses; a literature review component, an owner survey component, and a survey of bridge product producers. The objectives of these research efforts were to collect a broad base of information on the general problem of bridge deficiencies; ascertain the current practices of bridge owners, both state and local; and acquire information on some of the potential maintenance, rehabilitation, and replacement products that might be used effectively in the management of a diverse bridge network.

Literature Review

The literature review for this project was extensive, with various on-line databases being consulted. The resources of the TRB Transportation Research Information System database, the Engineering Index Compendex, the Applied Science and Technology Abstracts, and Dissertation Abstracts were among those consulted. In general, there is little specific information published that focuses on the topic of off-system bridges or, for purposes of this study, the concept of "low-volume" road bridges. Generally the focus of academic work is not in this area. Considering more generic information found in the engineering press, publications such as *Public Roads*, *Better Roads*, *Engineering News Record*, etc., there is relevant information describing innovative solutions to the problem to be studied, but the references occasionally lack sufficient detail. One of the challenges was to search for research and general information publications that describe projects whose objectives could be construed as having an impact on the engineering, construction, and management of off-system bridges.

This report does not contain a distinct literature review chapter, but rather discusses relevant references in many sections throughout the text. There are some relevant references that have been found in the process that specifically address the problems of low-volume road bridges. A brief description of several of these follows.

NCHRP Reports 222 (*Bridges on Secondary Highways and Local Roads Rehabilitation and Replacement*) and *243* (*Rehabilitation and Replacement of Bridges on Secondary Highways and Local Roads*) (University of Virginia 1980, 1981) are companion reports specifically addressing the problems of bridge rehabilitation and replacement on low-volume roads. Both of these reports were products of NCHRP Project 12-20, "Bridges on Secondary Highways and Local Roads—Rehabilitation and Replacement." The focus of the project was to identify common local road bridge deficiencies, evaluate feasible corrective procedures, evaluate economical bridge replacement systems, and develop decision trees to help assist local agency engineers in making repair or replacement decisions.

Both NCHRP reports can be considered precursors of this work, and complimentary to it. Although somewhat dated, most of the information in the two reports is still pertinent and is supplemented by the information in this synthesis. These reports should be part of the library for bridge engineers involved in bridge rehabilitation and replacement. They can be particularly useful to local bridge design and maintenance engineers whose contact with the "state of the art" is sometimes limited.

NCHRP Synthesis of Highway Practice 53: Precast Concrete Elements for Transportation Facilities (1978) focused on the use of precast concrete elements in the construction of transportation facilities, primarily bridge structures and highway appurtenances. Much has changed in the area of precast concrete structures in the 25 years since the publication of this report; however, the general description of precast products, their advantages and disadvantages, and the methods of fabrication and construction are still valuable in the general sense to the engineer considering the use of precast concrete products in a bridge rehabilitation or replacement project.

Wipf et al. (1994) presented research results concerning the evaluation of suitable options for county bridge replacement and also developed new bridge concepts based on the desired characteristics of county bridge replacements. The study endeavored to determine the reasons for bridge replacement, bridge replacement types and costs, participation of local forces in design and construction, expected life, foundation types, and the degree of satisfaction of county bridge owners with various bridge types. Following the information gathering process, several new bridge types were developed that met the objectives of county engineers. Additionally, standard solutions already in use were presented along with a brief discussion of the design and construction characteristics of each type.

Bridge Owner Survey

A key component to this NCHRP synthesis was the collection of information from industry members, traditionally bridge owners. A survey was developed as part of the project and then circulated to various potential respondents, including state DOTs, county and local bridge owners, and consultants involved with off-system bridge design and rehabilitation. The National Association of County Engineers (NACE) assisted in disseminating the survey to all potentially interested parties. Several hundred surveys were distributed electronically.

Because of the scope of this synthesis, a general study of off-system bridge issues, the questionnaire was broader based and intended to acquire more general information than questionnaires developed for more specific synthesis topics. Because the questionnaire was broad in nature and of reasonable length so that a high response rate could be obtained, the depth of inquiry in any one particular area of interest was limited. Specific areas of inquiry were

- General information (number of bridges and conditions),
- Structure design criteria (for new bridges),
- Highway design criteria (for new bridges),
- Bridge types (for new bridges),
- Maintenance (policies),
- Maintenance and rehabilitation options,
- Design criteria and funding, and
- Regulatory agencies (coordination with oversight and permitting agencies).

A total of 20 states and 70 local agencies from across the nation responded to the survey. State DOTs responding included Arizona, Arkansas, Colorado, Connecticut, Hawaii, Illinois, Louisiana, Maine, Minnesota, Mississippi, Montana, New Jersey, New York, North Dakota, Pennsylvania, Tennessee, Texas, Vermont, West Virginia, and Wyoming. Responses were received from local agencies in the following states: Alabama, Illinois, Iowa, Kansas, Maryland, New York, North Dakota, Ohio, Oregon, and Washington.

Of the responding states only Pennsylvania, Tennessee, and Texas are in the top 20% for total bridge population. None of the state DOTs responding are in the top 20% with respect to local bridge ownership as a percentage of the total state bridge count. However, this report will be of interest to all state DOTs involved in administering local bridge programs or in interacting with local agencies.

Some of the local agency respondents are from states with large off-system bridge populations; Illinois, Iowa, Kansas, and Ohio are in the top quintile of locally owned bridges by count and by percentage. Considering the significance of these states, the local agency responses are from the states that have significant concerns with local bridge management issues.

General data from the survey responses are presented here, whereas detailed discussions of specific survey responses are presented throughout this synthesis. A copy of the survey as well as tabulated responses are presented in Appendix A.

Bridge Product Manufacturer Information Collection

Although this synthesis does not in any way endorse or show preference for specific commercial products, it provides significant information on the various prefabricated and pre-engineered bridge products and also discusses some of the common software programs, design aids, etc., that are currently being used for off-system bridge design, construction, and maintenance. The volume of such information is a problem. The complexities of the job, reduced staff, ineffective dissemination of successful concepts, and so forth, make it difficult to determine the best practices to employ in the field. By synthesizing information relative to bridge products, bridge owners may have a larger "toolbox" of options to select from in the future.

REPORT ORGANIZATION

To address thej projects' many objectives, this report is organized into several chapters, each focusing on a distinct aspect of off-system bridges. The report is considered to not only be a summary of the current practice but is intended to be used by bridge engineers and administrators as an "owners manual" or "users guide" for their bridges. It is much more than a summary of practice in that it places many related off-system bridge issues in a single useful document. The remaining chapters are organized as follows.

Chapter two presents information related to the existing conditions of the bridge infrastructure, as well as a discussion of design policies and bridge finance needs. Although some of this information is widely known or cited in various sources by others it serves to make the case for an effective bridge design, construction, maintenance, and management approach for off-system bridges.

Chapter three is a comprehensive treatment of bridge maintenance, rehabilitation, and strengthening. It contains results from the project survey and an extensive review of previous research and demonstrated practices in the field. It also provides an extensive list of references for engineers regarding the various processes. Sufficient details are provided so as to be useful as a stand-alone document.

The topic of off-system bridge replacement is presented in chapter four. The chapter briefly discusses previous work in the area, but is a significant update to *NCHRP Reports 222* and *243*, which are more than two decades old. Results from the survey relative to bridge replacement are presented as are several sections summarizing the results from the literature review. An additional part of chapter four is devoted to discussing the various standard design plans, design aids, and software packages that are well-suited to off-system bridge engineering, design, and construction.

Chapter five is intended for bridge administrators rather than design or maintenance engineers, and it addresses the various administrative challenges unique to off-system bridges. Among the issues discussed are the use of bridge and asset management systems; various funding mechanisms available to bridge owners for bridge replacement, rehabilitation, and maintenance; a review of the environmental permitting process; and discussion of interagency partnering. These administrative problems are frequently cited in the survey responses and in the literature as significant issues that need to be addressed.

Finally, chapter six provides the project summary, reiterating some key points and drawing several conclusions from the study.

Two appendixes are included. In Appendix A the reader will find a tabulation of the survey responses. Appendix B provides a listing of available software for various aspects of bridge engineering. These programs, in addition to the various design aids discussed in chapter four, are particularly valuable to bridge engineers designing the various types of structures commonly found on off-system roads.

CHAPTER TWO

EXISTING CONDITIONS

There are approximately 587,000 bridges [structures longer than 6.1 m (20 ft)] on public roads, as reported in December 2000 NBI data made available by the FHWA (2000). Approximately 20% of the nation's public road bridges are located on NHS highways. Bridges owned by other than state agencies (i.e., city or county owned) constitute 54% of the nation's bridge population. Bridges located on routes not classified as Federal-Aid Highways (i.e., those on local roads or rural minor collectors) number approximately 283,000, or 48.5% of the public road total. Regardless of the definition of on/off-system, a majority of the nation's bridges are on roads with low to medium volumes and are typically owned by local agencies. Additionally, the NBI data only address "bridges"; that is, structures typically more than 6.1 m (20 ft) long. Statistics are not available on shorter structures.

Although the focus of this study is primarily on exploring maintenance, rehabilitation, and replacement options for off-system bridges, an examination of the existing bridge population is important in understanding the nature of the problem and guiding future maintenance, rehabilitation, and replacement efforts. Additionally, current levels of financing will be discussed in the context of maintaining the status quo and in the context of improving the road and bridge network over time. Finally, current standards for both geometric and structural design of new off-system bridges will be briefly discussed. Additional information on this issue is presented in chapter four.

STATE OF THE EXISTING POPULATION

In their annual report to Congress, the U.S.DOT, specifically the FHWA and the FTA, present facts and figures relative to the performance of the nations roads, bridges, and mass transit facilities. A summary of some of the relevant statistics from the *1999 Status of the Nation's Highways, Bridges and Transit: Conditions and Performance Report to Congress* (1999) is presented in this synthesis. Additionally, much of the information presented herein comes from various FHWA websites, reports, and an analysis of the CD-ROM version of the year 2000 NBI data.

Bridge Ownership Statistics

State agencies are the single largest owner of bridges, with approximately 269,000 (46%) of the national total. The second largest group of owners is county highway agencies, with approximately 233,000 bridges under county control (40%). City or municipal owners are next with approximately 35,000 bridges (6%), and an additional 28,000 bridges (5%) are under town or township control. In addition, there are other owners such as various federal agencies and toll authorities. The total number of non-state-owned bridges is approximately 317,000 or 54% of the national total. (See Table 1 for details on bridges by state and a breakdown of ownership.)

Several observations have been made regarding bridge ownership data. The states that are statistically in the top quintile for any category are highlighted in bold in Table 1 for ready identification.

States with the highest numbers of bridges are not necessarily those with large populations. Although heavily populated states such as California, Illinois, Ohio, Pennsylvania, and Texas are 5 of the top 10 in terms of total bridge population, Iowa, Kansas, Missouri, Oklahoma, and Tennessee, largely rural and agricultural states, are also in the top 10. The large numbers of bridges in the more rural and less populated states in particular present a difficult challenge as the funding of maintenance and replacement of large numbers of bridges is difficult with limited local tax bases or other means for raising the local matching revenue.

The number of off-system bridges, whether classified as non-NHS structures or by another appropriate method such as non-state-owned or non-Federal-Aid Highways is the primary interest in this study, not the total number of bridges. Many of the same states can be found on the list of the greatest number of non-NHS bridges, non-NHS bridges by percentage of total bridges, non-state-owned bridges, and non-state-owned bridges as a percentage of total bridges. More than 90% of the bridges in Iowa, Kansas, and Nebraska are located on non-NHS roadways, and all 10 of the statistical leaders in the non-NHS category could be considered rural states. For the states with the highest numbers of non-state-owned bridges, many of the same states are again on the list, with both Iowa and Kansas having in excess of 20,000 non-state-owned bridges; more than 80% of the bridge total in both states. The non-state-owned bridges in the top 10 states alone represent more than 27% of the nation's bridges.

Compounding the difficulties of the sheer number of bridges, especially their concentration in a number of

TABLE 1
BRIDGE OWNERSHIP—STATE AND NON-STATE OWNED, 1999 FHWA DATA

State	State Owned	Non-State Owned	Non-State (%)	State (%)
Alabama	5,494	10,142	65	35
Alaska	717	686	49	51
Arizona	4,146	2,275	35	65
Arkansas	6,927	5,568	45	55
California	11,598	**11,810**	50	50
Colorado	3,404	4,511	57	43
Connecticut	2,765	1,399	34	66
Delaware	774	37	5	95
District of Columbia	208	59	22	78
Florida	5,104	5,412	51	49
Georgia	6,359	8,005	56	44
Hawaii	675	389	37	63
Idaho	1,248	2,779	**69**	31
Illinois	7,520	**17,865**	**70**	30
Indiana	5,076	**12,911**	**72**	28
Iowa	3,993	**20,696**	**84**	16
Kansas	4,803	**21,116**	**81**	19
Kentucky	8,739	4,597	34	66
Louisiana	7,752	5,747	43	57
Maine	1,732	625	27	73
Maryland	2,457	2,440	50	50
Massachusetts	2,913	2,063	41	59
Michigan	4,268	6,358	60	40
Minnesota	3,454	9,278	**73**	27
Mississippi	5,310	11,367	68	32
Missouri	9,831	**13,375**	58	42
Montana	2,102	2,883	58	42
Nebraska	3,416	**12,110**	**78**	22
Nevada	937	451	32	68
New Hampshire	1,262	1,088	46	54
New Jersey	2,343	3,998	63	37
New Mexico	2,884	782	21	79
New York	7,390	9,876	57	43
North Carolina	15,820	852	5	95
North Dakota	1,096	3,439	**76**	24
Ohio	8,747	**19,059**	69	31
Oklahoma	6,663	**16,139**	**71**	29
Oregon	2,627	4,619	64	36
Pennsylvania	14,615	7,411	34	66
Rhode Island	591	157	21	79
South Carolina	8,207	861	9	91
South Dakota	1,792	4,243	**70**	30
Tennessee	7,811	11,545	60	40
Texas	31,274	**16,303**	34	66
Utah	1,660	1,071	39	61
Vermont	1,073	1,630	60	40
Virginia	11,245	1,403	11	89
Washington	3,034	4,787	61	39
West Virginia	6,354	321	5	95
Wisconsin	4,733	8,608	65	35
Wyoming	1,947	1,156	37	63
Puerto Rico	1,774	277	14	86
Total	**268,664**	**316,579**	**54**	**46**

Notes: Totals in bold are in the top quintile for non-state-owned bridges.
[*Source*: *1999 Status of the Nation's Highways, Bridges . . .* (1999).]

smaller states, is the issue of bridge age and progressive deterioration. Figure 1 depicts the trend in bridges built over specific time periods. The data include both state-owned and non-state-owned bridges. It reflects the large spike in the post-World War II (WW II) period corresponding to the institution of the Interstate highway program. It also illustrates that with the exception of the period from 1941 to 1945, a time in which most industrial efforts were focused on war production, one needs to go back to the period of 1926 to 1930 to find a time when fewer total bridges were built than in the recent time period of record, 1996 to 2000. Again, with the exception of the small upturn in the late 1980s, nationwide bridge construction has declined for every 5-year time period since the early 1960s.

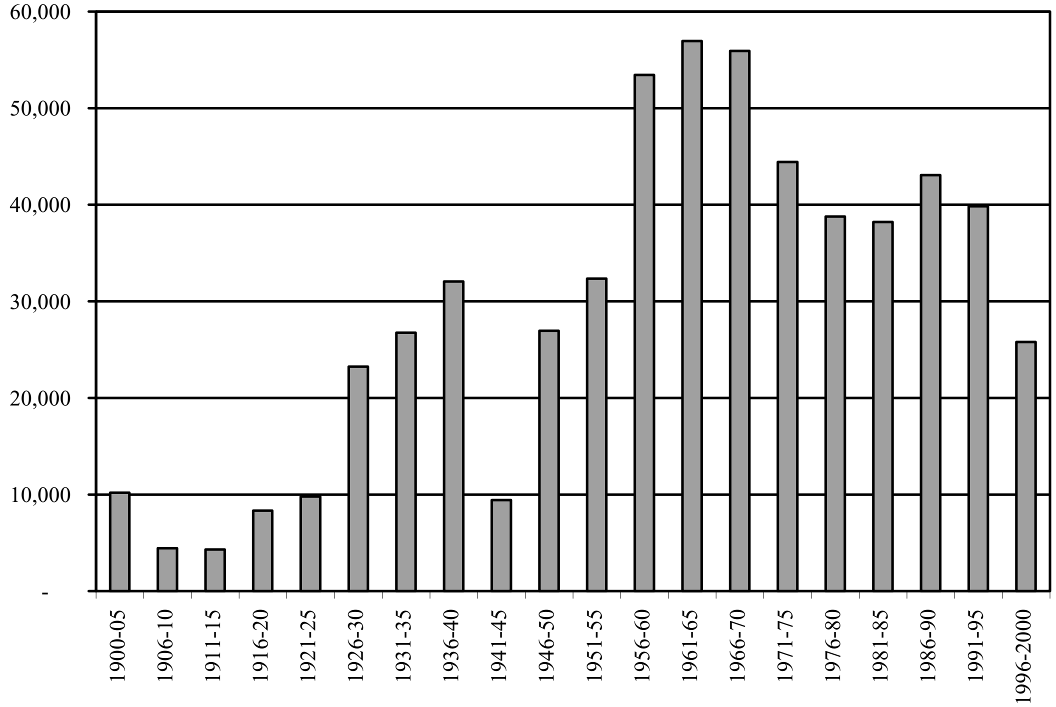


FIGURE 1 Number of existing bridges built in a specific time period.

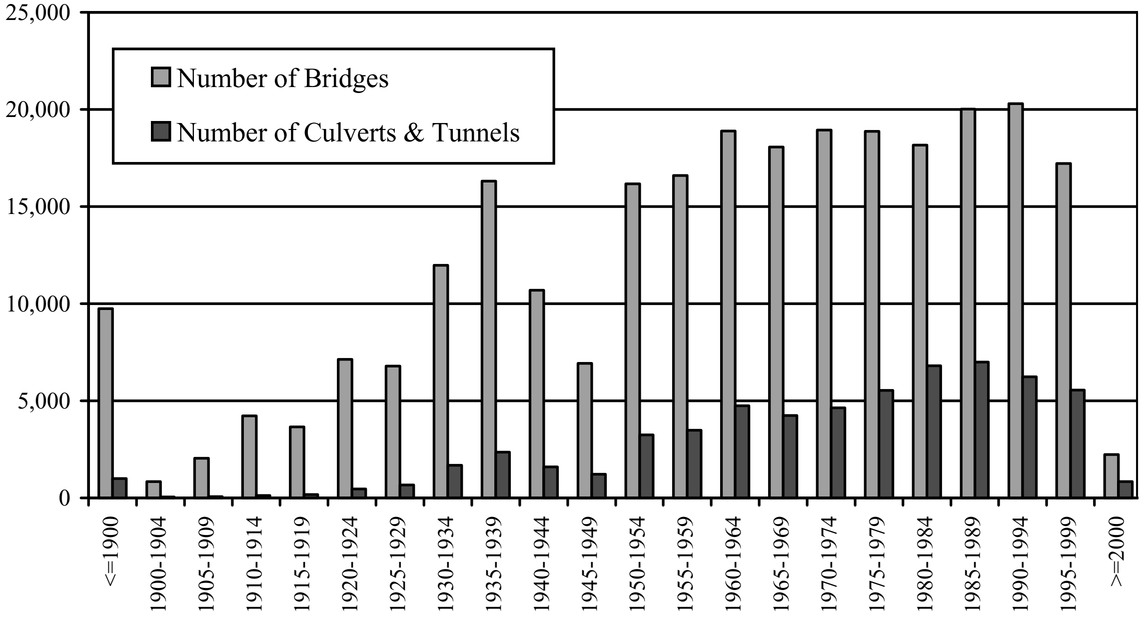


FIGURE 2 Number of non-state-owned structures built in a specific time period.

The large peaks in the post-WW II era are obviously a reflection of the rapid expansion of the U.S. population and its geographic dispersion away from traditional city centers. In addition, a significant number of the bridges constructed in that period were part of the construction of the Interstate Highway System; therefore, these data are not the most relevant depiction of the age of off-system bridges.

Figure 2 depicts the trend as it relates to construction on non-state-owned highways. Note that the trend does not have the large spike in the data in the 1950s and 1960s, but shows a steadier pattern of bridge construction and replacement. Nevertheless, even with some marked improvements in the past decade in reducing the number of structurally deficient and functionally obsolete bridges in the inventory, the current population is still an aged one.

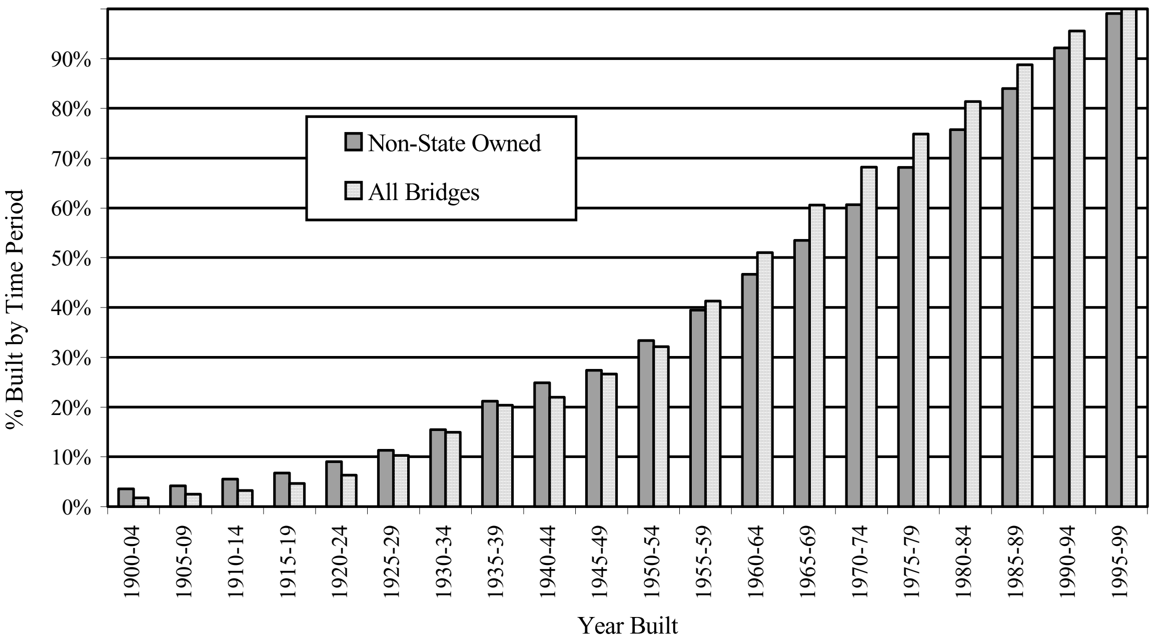


FIGURE 3 Percentage of total bridges built by specified time period.

When these data are plotted as a cumulative curve of bridges constructed over time, as in Figure 3, it can be observed that approximately one-half of the nation's total bridges are more than 35 years old and 20% are pre-WW II, more than 60 years old. The age distribution of non-state-owned bridges is very similar to the total bridge population, with one-half of these bridges being more than 40 years old and 20% dating to before WW II. Reiterating what was stated in chapter one, there are more than 12,000 bridges currently in service that are more than 100 years old. Of these, approximately 90%, or roughly 10,700 bridges, are owned by other than state highway agencies. Considering that deterioration rates appear to accelerate rapidly following 50 years of service, a large percentage of the existing bridge population will soon be this age and add significantly to the existing problem.

Bridge Deficiencies

An examination of the bridge types currently in service and their associated deficiencies is presented here. These deficiencies are examined both as they relate to ownership and also as they pertain to the type of construction and the type of roadway on which the bridge is located. A study of the deficient bridges, their owners, and the location of the bridges reveals several interesting trends.

Data from the FHWA ("Highway Bridges Dec–00," 2001) indicated that as of December 2000, the combined number of structurally deficient and functionally obsolete bridges was 28.5%, a slight reduction from the previous years' combined results of 29.6%. There is a nearly even split between bridges that are rated either structurally deficient or functionally obsolete. There are marked differences between the sufficiency of bridges on the NHS and those off system. Referencing the December 2000 NBI data again, for NHS bridges, the number of structurally deficient bridges is approximately 6,700, or less than 6% of all bridges on the NHS. Approximately 18,000 bridges are classified as functionally obsolete, less than 16% of the NHS inventory. The combined number of deficient bridges is 21.5% of the total number of bridges on the NHS. For non-NHS bridges, almost 80,000, or 17% of the off-system total, are structurally deficient, and 63,000, 13% of the off-system total, are functionally obsolete. The total deficiency is nearly 143,000 bridges, 30% of the total of off-system bridges.

The breakdown of bridges by type of owner, and the percentage of a particular owner's bridges considered structurally deficient or functionally obsolete, is presented in Figure 4. As the data indicate, with the exception of a small but largely deficient bridge population owned by private entities, local ownership has the highest percentage of structurally deficient bridges, whereas federal ownership has the highest percentage of functionally obsolete bridges. In general, urban bridges are more likely to be deficient than bridges in rural areas, 32.5% versus 28.8%, although rural bridges outnumber urban bridges by roughly a 4:1 margin. Generally, in the period from 1992 to 1999, the percentage of bridges considered structurally deficient has declined noticeably, from 20.6% to 16.0%, whereas there has been little change in the percentage of bridges considered functionally obsolete, 14.0% to 13.6%.

As shown in Figure 5, using the functional classification system is another convenient way of analyzing bridge

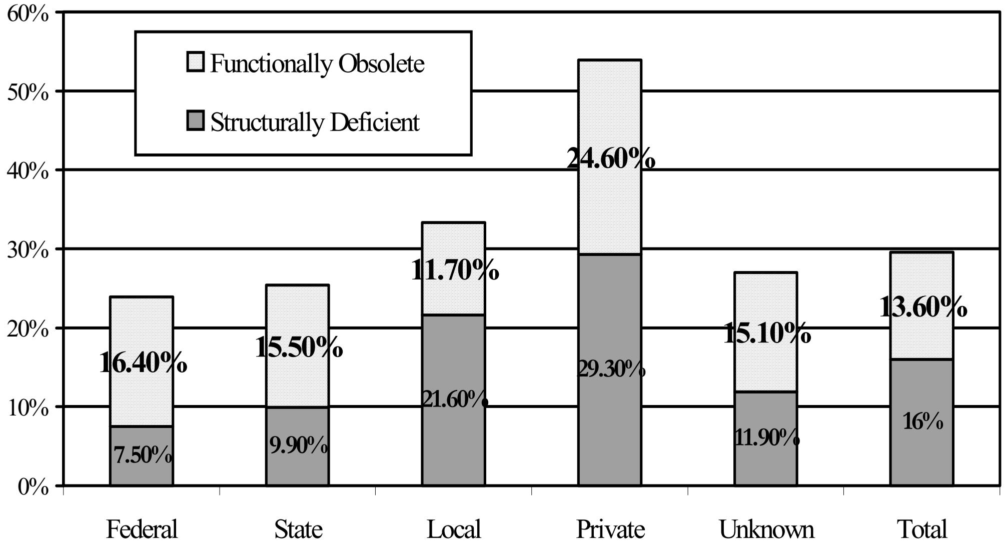


FIGURE 4 Bridge deficiencies by owner (*1999 Status of the Nation's Highway, Bridges . . .* 1999).

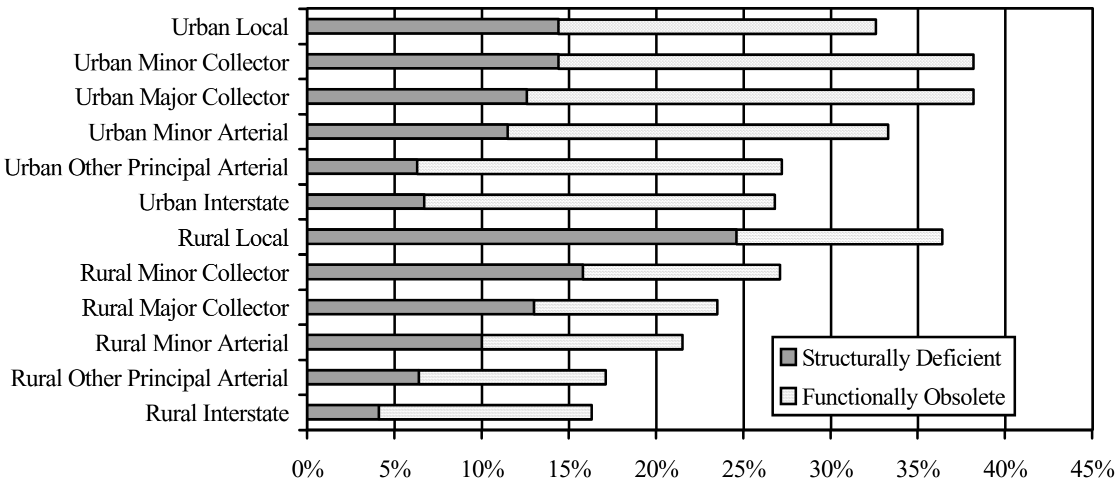


FIGURE 5 Bridge deficiencies by road type (*1999 Status of the Nation's Highways, Bridges . . .* 1999).

problems on various route types. Generally, the percentage of bridges likely to be deficient is lowest on the Interstate Highway System and increases with lower-level functional classification, with local roads having the highest percentage of deficiencies as well as the vast majority of total bridges. Consistent with the deficiency percentages being higher for urban bridges than rural bridges, most of the urban functional classifications have deficiency percentages greater than their rural counterparts, with the Urban Minor and Urban Major Collector categories having deficiency frequencies in excess of 38%. Note that by using the definition of off-system bridges provided by 23 USC 101; that is, local roads and rural minor collectors, these road types have bridges with some of the highest rates of deficiencies. Using this definition, this amounts to approximately 283,000 bridges or 48.5% of the nation's bridge inventory. Of these bridges, 22.2% are rated structurally deficient and an additional 12.3% are rated functionally obsolete, a combined deficiency of 34.5%.

Bridge Types and Associated Performance

A breakdown of bridge deficiencies by type of construction is also presented. There are numerous studies in the literature noting the superiority of one type of construction versus others. The intent of this synthesis is to present information on the current bridge population and not to endorse a particular type of construction. In general, with the quality of materials currently available, most structures, if detailed and constructed properly with low maintenance features, should provide adequate life.

TABLE 2
BRIDGE TYPES AND DEFICIENCIES FROM AUGUST 2000 FHWA NBI DATA

Bridge Type	Total Bridge Count	Type Structurally Deficient	Type Functionally Obsolete
Slab	76,803 (13.07%)	7,381 (9.61%)	9,622 (12.53%)
Stringer/multi-beam or girder	251,129 (42.74%)	49,835 (19.84%)	40,427 (16.10%)
Girder and floor beam system	8,880 (1.51%)	3,283 (36.97%)	2,025 (22.80%)
Tee beam	38,502 (6.55%)	5,098 (13.24%)	8,816 (22.90%)
Box beam or girders (multiple)	42,739 (7.27%)	1,996 (4.67%)	5,069 (11.86%)
Box beam or girders (single or spread)	6,547 (1.11%)	275 (4.20%)	683 (10.43%)
Frame (except culverts)	4,786 (0.81%)	385 (8.04%)	1,366 (28.54%)
Orthotropic	396 (0.07%)	64 (16.16%)	97 (24.49%)
Deck truss	801 (0.14%)	321 (40.07%)	162 (20.22%)
Thru truss	16,375 (2.79%)	10,427 (63.68%)	2,815 (17.19%)
Deck arch	7,544 (1.28%)	1,793 (23.77%)	2,397 (31.77%)
Through arch	384 (0.07%)	102 (26.56%)	104 (27.08%)
Suspension	102 (0.02%)	37 (36.27%)	40 (39.22%)
Stayed girder	25 (0.00%)	0 (0.00%)	2 (8.00%)
Movable lift	168 (0.03%)	46 (27.38%)	64 (38.10%)
Movable bascule	487 (0.08%)	142 (29.16%)	147 (30.18%)
Movable swing	250 (0.04%)	102 (40.80%)	83 (33.2%)
Tunnel	88 (0.01%)	4 (4.55%)	54 (61.36%)
Culvert	115,047 (19.58%)	2,827 (2.46%)	5,031 (4.37%)
Mixed types	459 (0.08%)	132 (28.76%)	80 (17.43%)
Segmental box girder	127 (0.02%)	4 (3.15%)	13 (10.24%)
Channel beam	12,895 (2.19%)	2,000 (15.51%)	1,002 (7.77%)
Other	2,974 (0.51%)	827 (27.81%)	764 (25.69%)

A detailed list of existing bridge types is presented in Table 2. These data come from the FHWA ("Bridges by Structure Type" . . . 2001). There are several observations about the performance of these various bridge types that can be used in future bridge construction.

The majority of the nation's bridges are of the multi-beam type. These include the traditional steel and prestressed concrete (P/C) stringer bridges as well as other stringer bridges, such as those with timber stringers. Nearly 43% of the nation's bridge total, slightly more than 251,000, is of this type. In second place are culverts, with close to 20% of the total, and in third are slab bridges, with approximately 13% of the national total. Although there are many other types of bridges, no other bridge type exceeds 10%.

Using the national average of deficient bridges of approximately 30% as a benchmark for assessing the relative merits of each type of construction, some bridge types can be considered to be better performers than the average and others worse. For instance, approximately 36% of the stringer/multi-beam or girder type are deficient and more likely to be structurally deficient than functionally obsolete. However, culverts, the second most popular type of construction, are only considered deficient 7% of the time, more than four times better than the national average. Of all bridge types, excluding cable-supported and movable bridges, only culverts, box beams, slab, and channel beam (inverted "U" shape) bridges have deficiencies less than the 30% of the national average. Conversely, multiple stringer, girder/floor beam system, tee beam, truss, and arch-type construction are either marginally or significantly more deficient than the national average. Some structure types such as truss and arch construction are more likely to be deficient because of their age. Neither structure has been a popular form of construction in recent years and age is a significant factor in their overall rating. Additionally, the through nature of some of these structures leads to roadway geometries likely to be considered deficient when evaluated using modern standards.

The bridges that are simple to construct (slabs, culverts, adjacent or spread box beams, and channel beams) rate better than the national average. They are also all well-suited for construction of many typical off-system bridges. By expanding the list somewhat to include bridges whose structural deficient percentage is less than the national average, 14.8%, open-frame and tee-beam bridges can be added to the list. These are also structures well-suited to the short and medium spans of most off-system bridges and, depending on local material availability, may be attractive options for bridge replacements. Many of the "well-performing" structure types lend themselves to prefabrication, standardization, and construction by local forces. They are also likely to be available as pre-engineered systems from local precasters.

Although data are presented for the percentage of bridges of various types considered to be functionally obsolete, no discussion is presented regarding this information. In general, functional obsolescence is not strongly correlated to structure type except as it relates to the geometric features of through structures where the bridge type is a defining characteristic.

BRIDGE FINANCE NEEDS

In 1997, the total spending for highway construction from all levels of government was \$101.3 billion, with the federal government funding 20.8%, states 52.1%, and local entities the balance of 27.1%. Of all the funds expended on highway construction, 48.1% was for capital outlay and an additional 20.6% for maintenance. The remaining funds are used for debt interest, bond retirement, policing, and administration. Of the capital outlay funds, approximately one-half was used for system preservation, 16% for new roads and bridges, 29% for other system expansion, and 8% for system enhancement.

Approximately 60% of the revenues collected and spent for highway work come from user fees such as motor fuel taxes and motor vehicle taxes. The other 40% of funds spent comes from property taxes, general funds, general taxes and fees, investment income, and bond proceeds. However, there is a significant difference in the source of revenue among federal, state, and local agencies, with almost all of the federal government revenue derived from user fees. States also collect most of their revenues from user fees, whereas local agencies collect little revenue from motor vehicle and fuel tax user fees, only 8%, with the balance of their revenue coming from property taxes, general fund apportionments, etc.

Of the money collected, a substantial portion is redirected for other uses. Using 1997 data, a total of \$89.9 billion was collected in user fees, whereas only \$64.7 billion was used for highway projects. Of the remaining \$25.2 billion, \$6.6 billion was used for mass transit projects and the remaining \$18.6 billion, or almost 22% of the amount collected, was redirected to various other government programs or deficit and debt reduction. It was also demonstrated that even if all of the highway user fee revenues were used for highway expenditures, that is, the entire \$89.9 billion, it would not cover the annual highway costs, \$101.3 billion, in the same year. Therefore, there is need for alternate funding mechanisms, particularly at the local level.

Given the 1997 figures on capital expenditures, including expenses such as highway improvements; right-of-way costs; engineering; construction of new bridges; bridge restoration projects; resurfacing, restoration, or rehabilitation (3R) projects; and construction-related activities other than maintenance, capital funds directed to rural and urban local roads, as well as the rural minor collector (off-system roads), were \$10.8 billion, or 22% of the \$48.7 billion total capital outlay.

For system preservation, activities such as bridge replacement, major and minor bridge work constituted \$6.1 billion of the total \$23.2 billion spent nationally on all systems combined. For new roads and bridges (system expansion), bridge expenditures were \$1.0 billion of the total of \$7.6 billion capital funds spent for new roads and bridges. In total, bridge expenditures were approximately \$7.0 billion of the \$48.7 billion of capital funds obligated in 1997, slightly more than 14% of the total funds obligated.

The estimated average annual "Cost to Improve Highways and Bridges" for the time period of 1997 to 2017 is \$94 billion. This includes \$83 billion per year to implement all beneficial highway improvements and an additional \$11 billion to eliminate all bridge deficiencies. The funds would be used at 51% for system preservation, 41% for system expansion, and 8% for system enhancement. Considering only the "Cost to Maintain Highways and Bridges," the average annual funding levels would be \$56.6 billion, with

$50.8 billion for maintaining current highway conditions and $5.8 billion for maintaining existing bridge conditions. Although existing conditions would be maintained, the net effect is that owing to increased traffic demands the overall system performance would decline.

The level of investment noted earlier, $48.7 billion in 1997, would need to be increased by 16% for the "Cost to Maintain" levels and approximately 93% for the "Cost to Improve" scenario. The projection in the 1999 Report to Congress was that with capital investment outpacing investment requirements, the Cost to Maintain funding level would be reached in 2003. The funding models indicated that if funding levels remain near where they are at the present time, there would need to be a shift of capital expenditures from system expansion to system preservation.

CURRENT DESIGN POLICIES

The engineering design process for off-system bridges is essentially the same for both state and locally administered bridges, with a mix of in-house and consultant services being used. Approximately 61% of state agencies design structures in-house and 72% indicated the use of engineering consultants. Only 44% of local agencies indicated that they use in-house engineering services for design, which is significantly lower than for state agencies. This reflects either a lack of engineering capabilities or inadequate time for design as opposed to more pressing maintenance and rehabilitation problems. The state agencies' standard bridge plans are used on only 22% of their off-system bridge replacements, whereas a significantly higher percentage of the counties, 45%, indicated the use of standard plans.

Survey recipients were also asked to briefly describe their agencies engineering processes for off-system bridge replacements. There were many different interpretations of this request and thus various types of answers.

Some respondents interpreted the question to refer to how bridges are chosen for replacement. These respondents indicated consideration of the general sufficiency of the bridge and consideration of ongoing rehabilitation costs. One specific response indicated that a bridge is identified for replacement when rehabilitation costs meet or exceed 70% of the replacement cost.

Other responses interpreted the question to refer to the actual process of engineering the replacement. There were differences in responses from state and local agencies. When commenting at all, state agencies tended to indicate the use of "fully-engineered" custom solutions for each bridge site. The designs were done by a combination of in-house staff and engineering consultants. Local agency responses indicated the much more frequent use of pre-engineered and reasonably simple solutions. Some of these bridges are designed internally and others are contracted out individually or handled by an on-call consultant. Both state and local agencies reported the use of a traditional process involving site survey, geotechnical and hydraulic assessment, creation of plans, fabrication, and construction.

Another common interpretation from agencies was that a response was requested as to bridge types or preferences. A theme among the local agency responses is the replacement of bridges with pipes or box culvert sections in lieu of a new bridge. This was indicated in several responses as the order of preference. When bridges are required, standard plans with pre-engineered beams, slabs, abutments, piling capacities, railings, etc., are commonly used, although, as one respondent indicated, ". . . this results in an over design for most applications but it simplifies plan preparation enough to save us time and money overall." Several local agency responses from Iowa indicated the use of Iowa DOT standard county plans. Other bridge types mentioned included the use of a standard nail laminated timber slab span for use in single spans or in multiple simple spans, use of timber or concrete slab bridges on salvaged abutments, sheet pile abutments supporting steel beams with corrugated decks and bituminous paving, and the use of wood and steel trusses for longer spans. Additional discussion on the choice of structure types for bridge replacement is presented in chapter four.

Geometric Design Policies

Agencies were queried as to their geometric design policies. It is a common concern that bridges wider than necessary are required by current design standards. The most commonly referenced set of guidelines for geometric design of highways is AASHTO's *A Policy on Geometric Design of Highways and Streets*, commonly referred to as the *Green Book*. A series of guidelines, but not a design manual per se, unless adopted by reference by a governing agency, the *Green Book* presents design guidance for the horizontal and vertical design of roads. *Green Book* criteria are routinely applied for the design of new or reconstruction of existing facilities. They are not intended to apply to the other types of common highway construction, routine highway maintenance, or the more common 3R projects. In such situations, where the changes to highway geometrics are usually minor and bridges are typically not replaced, the existing geometry may be maintained, insufficient by modern standards as it may be. The AASHTO *Green Book* is followed by 56% of state respondents and 70% of county respondents. Comments concerning geometric design policy included a statement from West Virginia that their local road design policy allows for bridge geometrics that are automatically functionally obsolete. Responses from Illinois, Maryland, and New York indicated the use of design policies specifically developed for local roads and low-volume bridges. Regarding published design exception policies, only 47% of state and 9% of local agencies indicated that published policies were in use.

Concerning design criteria in general, one of the issues explored in this project through the project survey is the area of concern for liability when other than the most current design criteria are used for new projects (or presumably allowed to be maintained during a 3R project). The specific question (see Appendix A, DCF-3) queried owners as to whether the reason for not using other than current design criteria was because of liability concerns. A total of 44% of state and 69% of local agency respondents indicated that legal liability concerns affect their decision to apply (or not apply) exception criteria.

There is general concern over the legalities of not following current design rules and an acknowledgement that it will take years to solve current inadequate structures and roadway geometries problems. One comment indicated that, in some cases, bridges that should be rehabilitated have not been because rehabilitation requires an upgrade of the structure to modern design standards, the cost of which is prohibitive. Fewer improvements are made because of this stipulation, certainly not the desired result of the federal funding programs that tie matching funds to the upgrading of structures to modern design standards. Other owners indicated that they knowingly spend much more money on bridge replacement than they believe is warranted as a safeguard against possible liability. There is no indication that state or local agencies believe in the construction of substandard structures; however, the implication is that a modified design standard for off-system or low-volume bridges may be appropriate.

Structural Design Policies

Structural design criteria are an issue that was raised with this synthesis problem statement. It was of interest to determine the current structural design policies of the agencies surveyed. Approximately 33% of state and 19% of local agency respondents indicated that structural design criteria other than the AASHTO *Standard Specifications* were used. Although not specifically asked what the modified design standard is (in lieu of the *Standard Specifications*), one can assume that it is likely that the AASHTO *Standard Specifications* with some exceptions were adopted by local agencies. When specifically asked if the agency had a published structural design exception criteria, 29% of state and 6% of local agencies responded in the affirmative.

In a more generic question (DCF-1), agencies were asked to comment on the need to develop revised design guidelines for low-volume road bridges. Several of the responses focused directly on the issue of design loading. Of the suggestions and requests submitted, there was included a suggestion for more low-volume road-appropriate bridge rails that are consistent with the design speeds and vehicle types found on such roads, suggestions that bridges built for wide vehicles on an infrequent basis need not be designed based on their width for multiple lanes of live load, and several responses in favor of the maintenance of minimum AASHTO loadings currently in use.

CHAPTER THREE

MAINTENANCE AND REHABILITATION/STRENGTHENING

INTRODUCTION

The objective of this synthesis is to provide bridge owners with information on bridges that are relatively inexpensive to design, build, and maintain. This chapter focuses on the maintenance of bridges to ensure adequate load capacity and efficiency for the safety of the traveling public. The term "maintenance" is often used generically to describe bridge repair activities, which also often raises the issue of rehabilitation and/or strengthening. In this chapter, a technical use of the term maintenance will be used. The specific terms maintenance, structural rehabilitation, and structural strengthening will be used technically, which requires qualification of their meaning. The following definitions are provided to clarify the terms as used in this synthesis.

Maintenance—The technical aspect of the upkeep of the bridges; it is preventative in nature. Maintenance is the work required to keep a bridge in its present condition and to control potential future deterioration.

Rehabilitation—The process of restoring the bridge to its original service level.

Repair—The technical aspect of rehabilitation; action taken to correct damage or deterioration on a structure or element to restore it to its original condition.

Stiffening—Any technique that improves the in-service performance of an existing structure and thereby reduces inadequacies in serviceability (such as excessive deflections, excessive cracking, or unacceptable vibrations).

Strengthening—The increase of the load-carrying capacity of an existing structure by providing the structure with a service level higher than the structure originally had (sometimes referred to as upgrading).

MAINTENANCE

Bridge maintenance can cover a broad range of topics. As noted previously, maintenance as discussed in this section refers to the technical aspect of the upkeep of bridges and is considered to be preventative in nature. A significant amount of general maintenance information has been developed and is available. The most useful information is in the form of manuals that have been developed by various bridge agencies and researchers that provide information on how to perform maintenance on particular bridge elements. Additionally, maintenance information related to isolated projects has often been published in the general literature. A number of different maintenance topics are presented in this section.

General Maintenance Information

NACE, with funding provided by the FHWA, publishes a number of useful guides for local bridge owners. Of specific interest to this project is the publication *Bridge Maintenance on Local Roads* (1995). The guide focuses specifically on general considerations for bridge maintenance, planning of maintenance activities, and provides various examples of common maintenance inspection techniques as well as concise examples of common repairs for typical bridge problems.

In the section on general considerations, this guide describes some of the usual maintenance concerns of a functional bridge population. The main emphasis is on the responsibility of the bridge population and the legal obligation to properly inspect and maintain or rehabilitate bridge structures even if they are not part of the federal road network. It is in this context of responsibility that the guide was prepared. All maintenance activities must be completed with adequate worker safety as well as proper notification of affected travelers. Additionally, the activities must be conducted after the appropriate permits are obtained, because some maintenance activities such as lead paint rehabilitation and bridge scour improvements may have potential environmental impacts.

It is emphasized that preventative maintenance such as routine cleaning and inspection is the key component to any bridge maintenance program. Effective bridge maintenance programs are those that are planned and systematic in their application. They typically involve the proper training of personnel in bridge inspection; the development of bridge maintenance inspection checklists; scheduling of both the inspection and any required maintenance activities; acquisition of proper vehicles, equipment, and supplies; and the incorporation of inspection findings and executed repairs into a comprehensive bridge management system. The NACE publication has two helpful checklists for bridge maintenance, one covering preventative bridge maintenance and the other a similar worksheet for culverts.

It is likely that agencies may already have similar worksheets; however, if that is not the case, development of a similar sheet or use of those supplied by NACE is recommended as a systematic means of acquiring data. A reproduced version of the NACE checklists for bridges and culverts is presented in Figures 6 and 7. In addition to the maintenance checklists, the NACE guide also lists suggested minimum equipment for the conduct of an effective bridge maintenance program, as well as suggested repair materials for the maintenance and repair of routine bridge deterioration.

The final section of the NACE guide provides simplified guidance on the inspection and maintenance of various bridge features including

- Signs and energy absorbing devices;
- Approaches;
- Substructures (concrete abutments and piers, timber piles and abutments, steel piling, concrete piling, and stone masonry abutments and piers);
- Trusses, truss members, and connections;
- Beam spans (timber stringers—treated or untreated, steel stringers and girders, concrete girders, bearings, and expansion joints);
- Decks (timber, concrete, steel, curbs, and sidewalks);
- Railings (concrete, steel, timber, and masonry);
- Waterways;
- Culverts and related appurtenances; and
- Cleaning and painting.

Although it is presumed that many agencies have standard maintenance procedures and methods of inspection, the NACE maintenance guide is a helpful tool to refine existing procedures or to help those small agencies with nonexistent or incomplete maintenance standards.

In 1998, a report was prepared for AASHTO officials through NCHRP. This report, *AASHTO Maintenance Manual—1998* (Brewer 1998), is based on previous AASHTO maintenance manuals and various AASHTO manuals for bridge maintenance. The 1998 manual summarizes information related to the process, methods, and materials used in maintenance operations in terminology familiar to persons new to roadway and bridge maintenance.

The manual uses a variety of tools to describe various aspects of bridge maintenance. Specifically, the manual uses common engineering terminology coupled with an extensive collection of sketches and engineering drawings to illustrate specific concepts. This combination of description and illustration provides an excellent reference on a wide variety of bridge maintenance topics. The report begins with a review of various bridge-related concepts, providing the user with a basic level of understanding. Detailed information on the maintenance of specific bridge components follows. The general bridge components discussed include

- Traveled surface,
- Structural decks,
- Superstructure,
- Substructure, and
- Watercourse and embankments.

Although the specific information presented for each of these components varies, the discussion for each follows the same general format. First, a general introduction provides information on the importance and use of each component, as well as a discussion of the general types of associated problems. Next, information on general preventative maintenance topics is presented. This typically provides the reader with information on what recurring maintenance should be done to maximize the bridge service life. Maintenance operations are then described with respect to a specific component. Information on other various bridge maintenance topics is also included, consisting of both general information that is applicable to many situations or very specific applications. These topics include

- Protective systems,
- Environmental aspects,
- Movable bridges,
- Maintenance workzone traffic control, and
- Use of nonmetallic materials.

The information presented within these topic areas basically supplements the previous information.

Realizing that the bridge inspectors in Florida were being asked to make recommendations for correcting maintenance deficiencies and that the recommendations made by inspectors varied significantly, the Florida DOT developed a manual for bridge maintenance (Roberts 1978). The intent of this manual was to provide inspectors with a tool for making better bridge maintenance recommendations. In addition, it was recognized that many of the DOTs' maintenance personnel were nearing retirement. The potential for a significant loss of knowledge and experience prompted the expansion of the manual to include step-by-step procedures for each repair. For each repair the following specific information is given:

- General application for the repair,
- Step-by-step instructions for completing the repair,
- Material specifications for the repair,
- Detailed drawings of the repair design,
- Detailed drawings of the construction details,
- Information on the use of traffic control,
- Safety precautions,
- Materials needed to complete the repair, and
- Measurement quantity for the repair.

BRIDGE PREVENTATIVE MAINTENANCE CHECKLIST

Structure No. __________ Route No. _____________ Date ____________

Feature Crossed ________________________ Inspected By _____________________

Bridge Length _________

Item	Satisfactory Condition	Needs Repair	Needs Engineering Study	Comments	Date Reported
SIGNING					
Advance Warning					
Load Limit					
Delineation					
WATERWAYS					
Debris in Stream					
Fences					
Islands or Sand Bars					
Erosion or Scour					
Berms					
Riprap					
APPROACHES					
Steep					
Rough					
Settling or Raising					
SUBSTRUCTURES					
Abutments					
Piers					
Piling					
Caps					
Bridge Seats					
Spalling (Abutment)					
Spalling (Pier)					
Paint					
SUPERSTRUCTURES					
Truss Broken					
Truss Bent					
Truss Rusted Out					
Stringers (Timber)					
Stringers (Steel)					
Steel Girders					
Concrete Girders					
Bearings					
Expansion Devices					
Expansion Joints					
DECKS					
Timber					
Concrete Girders					
Steel					
Curbs					
Sidewalks					
Railings					
CLEANING					
PAINTING					

FIGURE 6 NACE checklist for bridge preventative maintenance.

CULVERT PREVENTATIVE MAINTENANCE CHECKLIST

Structure No. __________ Route No. ______________ Date _____________
Feature Crossed ________________________ Inspected By _____________________
Bridge Length __________

Item	Satisfactory Condition	Needs Repair	Needs Engineering Study	Comments	Date Reported
METAL CULVERTS					
Headwalls					
Abrasion					
Pitting					
Connections					
Piping					
Settlement					
Cleaning					
CONCRETE CULVERTS					
Headwalls					
Box or Barrel					
Abrasion					
Joint Separations					
Piping					
Cracks (H&V)					
Settlement					
Erosion					
Cleaning					
RETAINING WALLS					
Alignment					
Cracking					
Weep Holes					
Erosion					
Joints					
Settlement					

FIGURE 7 NACE checklist for culvert preventative maintenance.

The following list summarizes the standard repair items given in the manual:

- Expansion dam repair,
- Expansion joint seal,
- Joint sealant repair,
- Beam saddle,
- Timber-stringer replacement,
- Painting structural steel—inorganic zinc,
- Painting structural steel—oil base,
- Concrete cap extension,
- Timber cap extension,
- Timber cap scabs,
- Timber pile replacement,
- Timber pile splice,
- Timber pile sway bracing,
- Shimming timber piles,
- Steel H-pile repair,
- Concrete pile jacket,
- Integral pile jacket (concrete),
- Integral pile jacket (steel),
- Timber helper bent,
- Helper bent,
- Crutch bent,
- Cathodic protection (zinc anodes—small), and
- Cathodic protection (zinc or aluminum anodes—large).

A study sponsored by TRB, described in *NCHRP Reports 222* and *243*, summarized various procedures for the repair, rehabilitation, and retrofitting of highway bridges. As stated in *NCHRP Report 243* (University of Virginia 1981), the first phase of this investigation, summarized in *NCHRP Report 222* (University of Virginia 1980), had four primary objectives

- To identify the common deficiencies found on bridges on secondary highways and local roads throughout the United States;
- To evaluate feasible corrective procedures that have been successfully employed for these deficiencies;
- To evaluate economical replacement systems for bridge structures for which repair or rehabilitation is not feasible; and
- To develop a simple procedure to assist engineers in making decisions involving repair or replacement.

The researchers found that a large percentage of bridge problems could be solved using repair, rehabilitation, and retrofitting procedures. *NCHRP Report 222* summarizes these findings. In addition, 27 highway bridge replacement systems were identified as being successfully used in highway bridge projects.

A number of topics were not addressed during the first phase of the work. Some of these items were purposely omitted to allow other relevant studies to be completed. It was therefore anticipated that the second phase of the research (summarized in *NCHRP Report 243*) would supplement the first. In addition, the second phase included information on two specific deck replacement projects: the New York Thruway Deck Replacement System and the replacement method used on the George Washington Bridge (New York).

The overall intent of the project was not to develop new methods or techniques. Rather, it was to synthesize the state of the art in a manner useful to persons directly responsible for bridge maintenance, rehabilitation, and replacement.

Iowa State University recently completed a study with funding provided by the Iowa Highway Research Board that contains useful information for maintenance, repair, and rehabilitation of bridges for local bridge owners. The report consists of two manuals for design and field implementation (Wipf et al. 2002) and focuses specifically on general considerations for bridge maintenance and rehabilitation issues associated with low-volume road bridges. Detailed case studies are included.

Unfortunately, as with many other states, Iowa has a large number of substandard bridges. The number of these deficient bridges will certainly increase unless some type of preventative maintenance is employed. These types of activities are referred to as maintenance, repair, and rehabilitation (MR&R). MR&R activities are used to keep bridge structures in their current condition and hence prolong their service lives.

The DOTs in many states and counties have successfully employed numerous MR&R procedures for correcting various types of deficiencies. However, for the same deficiency, the maintenance activities vary from county to county and from state to state. In other words, successfully employed MR&R procedures are not systematically defined for use by others.

Iowa has close to 90,000 miles of county roads, most of which are unpaved, low-traffic-volume roads. Eighty-two percent of the state's bridges are located on these county roads. This research study (Wipf et al. 2002) concentrated on the unique problems associated with these low-volume bridges. The primary objective of the project was to compile current information on MR&R techniques, implementation guidelines, and design details that are relevant to Iowa into a manual that would provide guidance for designers as well as field personnel involved in bridge MR&R on secondary roads.

The research project consisted of two phases: (1) the compilation of MR&R procedures that were relevant to the secondary road system in Iowa and (2) development of design guidelines (where pertinent or relevant) for the compiled procedures. To ensure that the research project would meet its ultimate objective, a project advisory committee that has representation from the Iowa DOT, county engineers, and municipal engineers guided the research effort.

The MR&R procedures presented in the manual provide information an engineer can use to resolve most of the problems on the local road system. Because a wide variety of problems are reviewed, the level of detail provided for the numerous MR&R procedures varies from conceptual ideas to detailed design guidelines.

The general tasks in completing the project included a review of existing literature and other pertinent references. A questionnaire was developed and disseminated to all 99 Iowa counties. The purpose of the questionnaire was to gather information on the MR&R issues that the county engineers encounter. Particular emphasis was paid to the problems faced and the solutions (if any) that were adopted. The questionnaires were followed up with visits to counties that had expressed an interest in discussing in greater detail the problems that they had and the solutions they had adopted. The MR&R activities were compiled and included in the manual. Essentially all areas of bridge maintenance, repair, and rehabilitation were reviewed and the accumulated information was categorized on the basis of activities related to different bridge components. The compiled information was summarized and presented in a manual and includes details of the field implementation of the various MR&R procedures and design guidelines where relevant. For each MR&R activity, a step-by-step procedure for accomplishing it, material specifications, and detailed drawings are provided.

Different techniques for the repair and rehabilitation of both superstructure and substructure elements, in varying degrees of detail, were compiled. MR&R procedures for 16 different superstructure-related problems and 9 different substructure problems were included. Details of these strategies were obtained from published literature or from the results of the questionnaires disseminated to the counties. The types of issues considered included the following:

- Superstructure components
  - Replacement of steel beams,
  - Installation of intermediate supports,
  - Repair of corrosion damage,
  - Addition of stiffening angles,
  - Installation of beam saddles,
  - Repair of truss members,
  - Bridge widening,
  - Repair of cracked timber stringers,
  - Timber-stringer replacement,
  - Repair of decaying timber deck planks,
  - Concrete deck patching, and
  - Installation of expansion joint seals.
- Substructure components
  - Maintenance of bearings,
  - Repair of sway bracing,
  - Shimming timber piles,
  - Pile splice,
  - Addition of supplemental piles,
  - Repair of steel H-piles,
  - Pile jacketing,
  - Pier widening,
  - Strengthening pier caps, and
  - Repair of abutments.

In addition to general field implementation guidelines, the following items include design guidelines based on the AASHTO Standard Specifications:

- Installation of intermediate support for steel girder bridges,
- Strengthening of steel beams with insufficient section,
- Installation of a beam saddle,
- Repair of cracked or split timber stringers, and
- Pier strengthening or widening.

To supplement the information collected in the literature and from the questionnaire, finite-element analysis of individual retrofitted and deteriorated piles were completed to investigate their stability. Nondimensional design curves were developed based on the results of the analysis. These plots were intended to aid the designer in deciding whether pile buckling or axial stresses would be the governing mode of failure.

Concrete Bridge Maintenance

A chapter in Mallett's *Repair of Concrete Bridges* (1994) describes repair techniques for concrete bridges. Topics covered in this chapter include patch repairs, treatment of cracks, use of sprayed concrete, special problems in concrete bridges, general repair options, concrete removal, issues with reinforcement, and types of repair materials.

A bridge rehabilitation project that was initiated in 1992 is described by Goldenberg (2000). The project was initiated as a result of observed damage to the expansion joints. Originally, the bridge owner thought this project would simply entail replacing the expansion joints and repairing any concrete damage. However, after review, it was decided that this approach would not resolve the problem of future water damage. As a result, design engineers proposed redesigning the bridge superstructure to eliminate the joints completely. This one-piece continuous slab would prevent water from damaging the substructure.

Barnaby (1996) described, through three case studies, the use of precast polymer concrete stay-in-place forms for the rehabilitation of concrete structures. He pointed out that polymer concrete is similar to conventional concrete, except that it uses polyester resins to bind the aggregate in place of a water–cement paste. Barnaby noted that concrete is three to four times stronger than conventional concrete and is virtually impervious to water. By means of the three case studies, bridge parapet panels, composite barriers, and pile jackets, Barnaby summarized the advantages of this specific type of stay-in-place concrete formwork.

A study conducted by the FHWA under the supervision of Virmani (1991), evaluated the condition of prestressed concrete bridges subjected to corrosive environments, evaluated commonly used conventional repair methods in a 4-year monitoring program, and made recommendations on the design and repair of prestressed concrete bridges to reduce their susceptibility to corrosion. The study consisted of a review of the technology related to corrosion-induced deterioration, the identification of a sample of bridges in various environments on which to perform experiments, and design and evaluation of commonly used repair techniques. The study resulted in several recommendations related to preventing and repairing corrosion-related damage.

Removal of Paint on Steel

The increasing costs of lead paint removal and repainting have become a significant burden for bridge owners. With the increased requirement for 100% containment, hazardous waste disposal, and health and safety plans as components to field repainting, the costs associated with maintaining older steel bridges may be prohibitive when compared with other solutions. There are instances where bridge replacement is more economical than bridge painting. There are also occasions where the removal of steel, blasting and repainting in a shop environment, and subsequent reconstruction of the bridge in place are more economical than field cleaning and repainting. This is verified by the experiences of the Connecticut DOT with several bridges (Castler 1994).

During a major infrastructure renewal program prompted by the collapse of the Mianus River Bridge, Connecticut embarked on a major bridge rehabilitation program, including the rehabilitation or replacement of more than 2,000 steel bridges. In the first 4 years of that program (1985–1989), the average costs for bridge repainting were \$17.43/m^2 (\$1.62/ft^2) of steel. The recognition of the need for containment resulted in the introduction of a 75% containment policy in 1990 resulting in a jump in costs to \$64.80/m^2 (\$6.02/ft^2). Subsequent changes to 100% containment and then 100% containment with a funded worker health and safety plan raised the costs of repainting in 1993 to an average of \$133.37/m^2 (\$12.39/ft^2). The alternatives to bridge repainting include steel replacement, zone painting, or overcoating. The zone painting and overcoating "solutions" are only temporary measures and do nothing to eliminate the underlying hazards. The decision to replace steel in older lead painted steel structures should be seriously considered, especially in situations where major deck rehabilitation is required. In rehabilitation projects where deck removal is not required, the amount of ancillary superstructure repair work and repainting should be compared with the costs of a new superstructure.

A sidebar to the article by Castler (1994) is presented by Kline (*Analysis of Steel Replacement as an Option*) documenting the analysis of various solutions to steel bridge rehabilitation. Spot painting costs averaged from \$10.76 to \$26.91/m^2 (\$1.00 to 2.50/ft^2) depending on the area to be painted. Zone painting, including the more extensive containment requirements, averaged \$43.06/m^2 (\$4.00/ft^2). Steel removal, blast cleaning, and re-erection costs \$65.35/m^2 (\$7.00/ft^2) in bridges where the decks are to be replaced. Finally, total containment and field repainting costs nationwide ranged from \$75.35 to \$129.17/m^2 (\$7.00 to \$12.00/ft^2). Kline concluded, based on 1993 in-place steel superstructure costs, that when repainting costs exceeded \$108/m^2 (\$10/ft^2) a new bridge may be more economical than repainting. This is of course tempered by the site constraints, but defines the point at which a new structure might be an economically viable option. When bridges are to be redecked and there is a significant amount of steel repair work, that is, corrosion repair, bearing replacement, etc., the choice of superstructure replacement is more likely the economical solution because of the high costs of miscellaneous steel field work. The decisions to rehabilitate and repaint or replace are heavily influenced by regional economic factors and should be based on current regional cost information.

NCHRP Synthesis of Highway Practice 251 (Appleman 1997) studied the various processes of lead-based paint removal including disposal, contractual requirements, environmental regulations, and contracting processes. Additionally, cost data for both overcoating and full paint removal and repainting were collected from state highway agencies. These costs generally supported the trends and cost figures reported previously by Castler. The data reported by Appleman are the result of cost data for nearly 4,400 bridges painted between 1993 and 1996 (93% of the bridges were coated with lead paint). The number of bridges undergoing full repainting was 1,709, and the balance of the bridges were overcoated. The average cost per bridge for overcoating was \$202,000, whereas for full removal the cost averaged \$256,000 per bridge. However, the average cost per unit area for overcoating is approximately half that charged for full removal, the implication being that the overcoating projects were nearly twice as big as the full removal projects. The data for full removal were highly varied, with the low cost being \$29.27/m^2 (\$2.27/ft^2) in Illinois, and the high cost \$243.80/m^2 (\$22.67/ft^2) in Maryland. The average cost is \$112.58/m^2 (\$10.46/ft^2) and the median is about the same. These averages are composed of costs from girder bridges, trusses, bascule bridges, and various structure types. Differentiating the costs further, the average cost for girder bridge full lead paint removal is \$83.39/m^2 (\$7.75/ft^2) and for trusses \$145.69/m^2 (\$13.54/ft^2); the truss cost being substantially higher because of the increased difficulty in removing and repainting truss members. Similar cost data are presented for overcoating. Most of the bridges that were overcoated had existing coating degradation of less than 20%. The overcoating costs for girder bridges varied from \$12.37/m^2 (\$1.15/ft^2) to \$118.36/m^2 (\$11.00/ft^2), with an average cost of \$46.59/m^2 (\$4.33/ft^2). For truss bridges, the costs ranged from a low of \$29.27/m^2 (\$2.72/ft^2) to a high of \$102.22/m^2 (\$9.50/ft^2), with an average expenditure of \$62.52/m^2 (\$5.81/ft^2). Data were requested on projects in which total steel removal was used in lieu of bridge painting; however, Appleman indicated that the number of projects in which this was reported was small and therefore data on these projects are not presented in that report. Work is cited however in that synthesis, including that of Castler, regarding the costs of repainting versus bridge replacement. Data presented from the North Carolina DOT indicated that the cost of deck replacement and full repainting exceeds that of constructing a new bridge by approximately 8%. In the event that repainting is a viable option, the possibility of full disassembling, shop cleaning, and repainting followed by re-erection should be considered as a possible cost-saving solution over in-place rehabilitation.

Bridge Railings

An important aspect of bridge maintenance and rehabilitation is bridge safety as it relates to bridge rails, as well as the approach railings leading to the structure. A publication prepared by the FHWA Office of Highway Safety and Office of Engineering (*Improving Highway Safety at Bridges* . . . 1998) for distribution by Local Technical Assistance Program (LTAP) centers is intended to illustrate common problems and solutions for bridge rails in local road applications.

Bridge and approach rails must, like bridges themselves, be structurally and functionally adequate. Bridge rails must have sufficient strength to withstand the impact from a specified design vehicle. Their functional adequacy depends on several aspects. A bridge rail must not redirect a car into adjacent lanes or oncoming traffic, must not snag the car and spin or overturn it, must not vault the car over the bridge or into portions of a rail not structurally capable of resisting the impact, and must not have features that could penetrate the vehicle. Similarly, approach rail structural strength must be such that there is an adequate connection to the bridge rail specifically in the transition area between the approach road and bridge deck area. The functional aspects of approach rails are the same as for rails anchored to the bridge with the addition that approach rails must also prevent the driver from leaving the roadway and striking roadside obstructions.

A significant portion of the FHWA publication concerns the identification of deficient rail types and gives specific reasons for their inadequacy. It is mentioned that eliminating inadequate bridge rails can be an expensive activity, especially if it is to be performed as a separate project from some other major bridge rehabilitation and reconstruction activity. It is suggested that retrofit of the inadequate rail system as a temporary measure may be more appropriate until such time that major rehabilitation is performed. However, it is stressed that the temporary railing retrofits should not be construed as permanent and in compliance with safety standards.

In terms of bridge rails, cable systems and approach roadway type guardrails are structurally inadequate for bridge railings. These flexible systems have the tendency to deflect and may allow a vehicle to strike the supporting posts. Additionally, inadequate connection features that may break away from the supporting bridge structure generally support them. Even bridge railings that are inherently structurally adequate may be inadequate in service because of extensive structural deterioration in the vicinity of anchorages. Bridge railings should have sufficient length to develop the required strength and should terminate back on the approach roadway in a fashion that does not allow for head-on collisions with the bridge railing.

There are also a number of features that lead to functionally inadequate bridge rails. Vaulting of a vehicle can occur when a low-level feature is present that catches a vehicle tire and sends it airborne. Such features include sidewalks or brush curbs. Snagging occurs on railings such as the older open baluster style rails, where a vehicle can get caught on the projections of the individual posts or the more prominent balusters. Redirection may occur if there is a discontinuity in rail shape, such as from the projection of a light pole support from the face of a railing. Discontinuous or missing rail elements can penetrate the passenger compartment. All of these potential problems may be remedied through either temporary or permanent retrofits.

Inadequate bridge rails can and should be improved in either a temporary or permanent fashion. The most obvious solution is to replace inadequate bridge rails with structurally and functionally adequate rails designed to modern standards. However, this may either be prohibitively expensive or impractical at the time. Additionally, it is important to recognize that railings of different levels exist and the appropriate level of a railing may not be the same for local or low-volume roads as for the more significant “Jersey” or “F-shape” rails that are designed for higher volumes, greater design speeds, and heavier vehicles. An upgrade of the existing rails may also be difficult as a stand-alone item if it results in the reconstruction of significant portions of the bridge deck or modifications to the supporting beams. One of the most effective solutions in terms of cost and overall effectiveness is to provide a new railing inboard and attached to the substandard rail. This new rail, which may be composed of a continuous thrie beam and supporting w-sections, can be used to contribute additional strength or prevent the impact of a car with some of the substandard vaulting or snagging features of common older railing systems. The new rails should be carried off the bridge into a similarly upgraded approach transition and fitted with a crashworthy end terminal.

Many of the same types of concerns exist with regard to approach railings. In many respects the approach railing may be more important to driver safety at many bridge locations than the bridge railing itself. Approach railings are generally required when an errant vehicle could collide with a projection above the road surface. Examples would include the blunt end of concrete bridge railings, culvert headwalls, and projections of through girder or thru truss bridges or roadside appurtenances in the vicinity of the traveled way. Additionally, an approach rail is needed in grade separation situations such that an errant vehicle leaving the road cannot proceed down an embankment into a lower road or stream under the bridge. Thus, an evaluation of the required length of an approach rail is necessary. The AASHTO *Roadside Design Guide* should be consulted for guidance in determining the length and orientation of approach rails as it relates to protection against striking roadside hazards.

The functional adequacy of an approach railing is determined by it ability to safely maintain the vehicle in the intended direction of travel while not snagging, vaulting, or otherwise redirecting the vehicle in an unintended fashion. Typically, railings flared away from the road at a 1:15 taper or flatter will not catch or inadvertently redirect a vehicle into an adjacent lane. The rail must be stiffened in the vicinity of the bridge railing so as not to "pocket," which would allow the car to strike the end of the bridge railing. The stiffening is typically accomplished through the addition of extra posts at the approach rail transition to the bridge. At the point where the approach railing is no longer needed, it too must be terminated. This should not be done with a blunt end but rather with a turned-down section located outside of the clear zone, so that a car cannot vault over the turned-down end. As an alternate to turned-down end sections outside the clear zone, one may wish to consider the use of a crashworthy terminal such as an impact attenuator at the end of the approach railing.

An additional safety feature that has a direct impact on bridge safety is the approach roadway itself. Appropriate signage in terms of location and size should be positioned at a location where the presence of a bridge is difficult to determine because of roadway alignment, vegetation, etc. Roadside object markers to better delineate the presence of bridges and culverts are valuable in both the summer months when vegetation might obstruct a driver's view and in poor weather conditions. One should endeavor to maximize the sight distance approaching a bridge. This is especially important when considering the many substandard bridge widths and safety features at current bridge locations.

Deferred Maintenance and Road Closure

Among the methods suggested as being effective in maximizing the usefulness of funds available to local road agencies is reduction of maintenance or the closure of some roads and associated bridges. Although deferring maintenance through the years is a prime contributor to the current state of the bridge population, there are still situations in which funds are simply not available to meet current demands and decisions need to be made regarding the ability to keep an existing facility open. Welte et al. (1997) provided a summary of a more detailed report on the legal implications of deferred maintenance and road closure as a potential liability issue for bridge owners. Their report specifically addressed the nuances of state law in North Dakota; however, the decisions they refer to in lawsuits are from federal court rulings.

In general, Welte et al. indicated that government agencies are immune from lawsuits arising from deferred maintenance or road closures as long as the actions taken were considered discretionary; that is, the decision made to defer maintenance, close a bridge, or post a warning sign, was not prohibited explicitly by statute. The possibility that actions will be considered discretionary in a court of law increase if an agency follows applicable statutes, presents a good faith effort to minimize public risk, and uses factors other than pure economics to make maintenance decisions (i.e., historical levels of maintenance and repair for a particular infrastructure component).

Emerging Technologies

The results of a field study on the effectiveness of externally bonded fiber-reinforced polymer (FRP) plates on a reinforced concrete bridge found that the retrofit was a simple and straightforward process that reduced reinforcing steel stresses from 4% to 12% and reduced girder deflections from 2% to 12% (Stallings et al. 2000). However, it was determined that classical cracked-section moment of inertia calculations revealed that the moment of inertia increased only by 5%. These results indicated that more advanced procedures are needed to accurately determine the benefit of FRP plates.

Bridge Owners Survey Results: Bridge Maintenance Needs

Bridge maintenance needs have been examined in this synthesis through resources found in the literature and through the use of survey responses to questions specifically focused on bridge maintenance. Of specific interest are those items that constitute the most significant problem in the opinion of bridge engineers and administrators. Survey items MA-3 and MA-4 were intended to acquire data about the most significant maintenance problems (see Figure 8).

As would be expected, bridge decks were determined to be the most significant maintenance problem, with approximately one-quarter of state and local agency respondents ranking decks as their most pressing maintenance concern. This is the result of both the exposure and direct loading they receive and also because of the low tolerance of the riding public to poor ride quality. More extensive deterioration of other bridge elements, although certainly as important if not more important to the overall structural integrity, is not perceived by the traveling public and therefore is not as high a priority. Following decks, both state and local agencies ranked bridge superstructures, substructures,

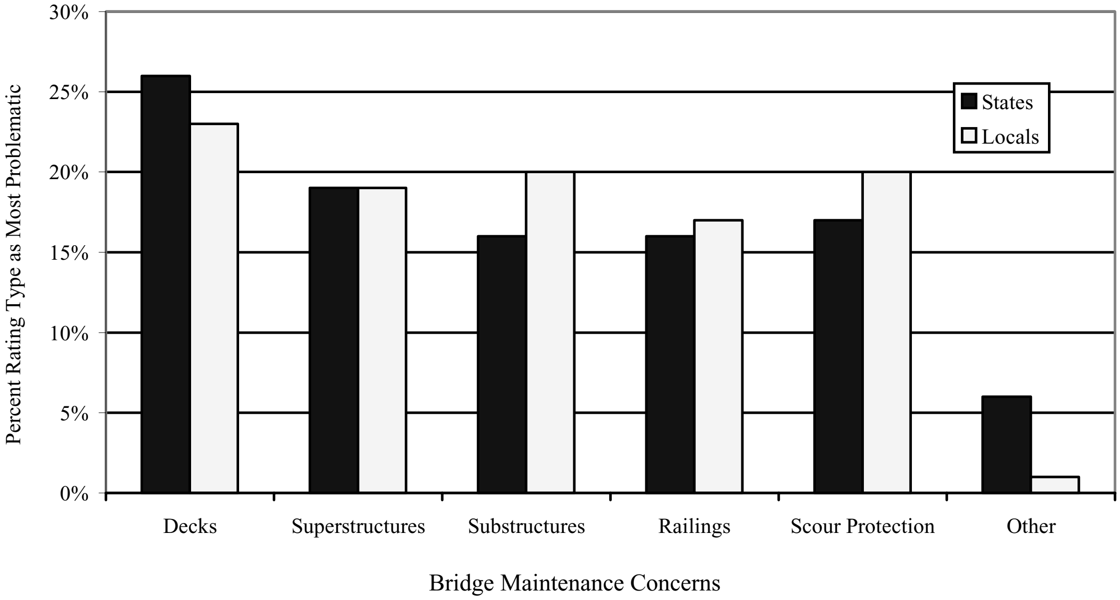


FIGURE 8 Bridge components causing the most maintenance problems.

bridge railings, and scour protection approximately evenly, with 15% to 20% of respondents noting that each of these items was the most pressing maintenance concern.

The most obvious problems with bridge decks are those related to deterioration. Responses pointed to bridge deicing salts as a key contributor to deck deterioration, along with the use of noncoated (or otherwise unprotected) reinforcing steel in older reinforced concrete bridge decks, which has resulted in various problems including deck delamination, spalling, scaling, potholes, punch through, and other deck failures. It was noted that in badly deteriorated concrete decks the choice between continuing to patch and completely replacing the deck is not always clear. Only limited responses regarding other deck types were provided; one comment indicating that the use of open deck bridge decks allows for natural flushing of the deck, whereas another discouraged the continued use of open decks because of the deterioration of the underlying superstructure. The only comment relative to timber decks was related to the need to repair or replace failed overlay riding surfaces.

The common superstructure deteriorations reported generally related to damage to the superstructure in the vicinity of open deck joints or near otherwise failed deck joints. Leaking deck joints commonly result in section loss or extensive deterioration in beam ends as well as the underlying bearings and beam seats. In addition to superstructure deterioration under leaking deck joints, older concrete structures are frequently subject to reinforcing bar corrosion and spalling, whereas older steel structures often have failures of the paint systems. Older structures may also have either narrow roadways or insufficient vertical clearance over another road, which can lead to damage from vehicular impacts. The repair of any or all of these superstructure deteriorations may be difficult and likely cost-prohibitive.

Substructure maintenance problems again are commonly related to the environment. Abutment and pier deterioration is frequently cited by survey respondents in the vicinity of failed joints and sometimes results in the loss of bearings. With respect to bridge substructures, failures cited included movements of abutments and piers. These failures are likely a function of several phenomena including malfunctioning substructure drains and loss of bearing capacity because of undermining or washout of bearing materials. Deterioration of sheeting used for abutment construction was also mentioned. Another common problem cited is the effect of localized footing scour. The presence of scour holes is a significant safety concern in many older structures and one that may be expensive to repair owing to the need to either dewater around damaged substructures or employ underwater construction techniques.

Bridge Owners Survey Results: Maintenance Reducing Procedures

The various bridge maintenance techniques currently in use were of interest to this project, given the state of the current bridge population concerning the number of bridges in need of repair, coupled with limited funding available to accomplish all needed work. It was anticipated that bridge owners have information that most likely is not in the literature. This information once collected and disseminated through this synthesis could be valuable to the bridge community. Some of the practices used by state and local agencies are presented herein. Some of the responses are not maintenance techniques per se, but are responses advocating the use of techniques in new bridge construction that lead to reduced maintenance in the future.

Consistent with the ranking of bridge decks as the most significant maintenance concern, many of the maintenance (or initial construction) techniques cited are those aimed at prolonging the life of decks, including

- Use of epoxy-coated reinforcing,
- High-performance or dense concrete mixes,
- Silica fume admixtures, and
- Increased cover.

Following construction, certain maintenance activities are also purported to extend the deck service life, including

- Periodic application of boiled linseed oil for the first several years of the deck's life,
- Use of penetrating concrete sealers,
- Annual washing of the bridge deck to remove accumulated debris and road salts, and
- Maintenance of bridge scuppers and drainage systems.

Some survey respondents favored the use of reduced salt application on bridges with a higher use of tractive materials, such as sand and slag or spray application of brine solutions.

There was also a variety of responses relative to bridge superstructure and substructure maintenance. Washing, previously cited as being effective in prolonging the useful life of bridge decks, was also cited in conjunction with superstructure maintenance. Accumulated debris can build up on superstructure beams and, if not periodically removed, can result in corrosion of the structure. Periodic washing is a simple solution to this potential problem. Maintenance activities related to bridge joint problems are also frequently cited. Such occurrences inevitably lead to problems with beam end deterioration and bearings and concrete deterioration at beam seat locations. The most common maintenance activities for substructures are those related to scour or activities related to protecting foundations. Periodic cleaning under bridge structures is advocated as promoting free flow and discouraging footing scour, and can be as simple as removing accumulated tree and brush debris on the upstream face of bridge piers. The use of riprap footing protection as well as the frequent inspection and upkeep of such protection, is important. There were a number of different responses on how to maximize the benefits of routine maintenance. All of the techniques can be broadly described as an attempt to arrest problems before they become significant rehabilitation issues.

Maintenance prioritization is a significant issue for state and local bridge owners, particularly in the context of budgetary pressures. Periodic monitoring of bridges is an effective way of reducing the number of needed repairs and thus the cost of such repairs. Several respondents indicated that maintenance inspections are performed more frequently than the traditional 2-year inspection cycle. In terms of prioritizing structures for maintenance, this is a combined effort using results from the NBIS bridge surveys, reports from bridge maintenance inspections, and other agency input. The grouping of structures with similar maintenance needs located in close proximity was mentioned as one means of reducing the maintenance costs. Many of the respondents perform a wide variety of maintenance activities with in-house workers. Some specialized activities mentioned as being performed in-house included heat straightening of damaged steel and gunite or shotcrete repair of damaged concrete. Painting is done; however, it was mentioned that it may be more economical to replace low-volume road bridges with significant painting needs than to rehabilitate them. Bridges that are high maintenance may be more effectively remedied by scheduling their replacement than continuing with expensive repairs. Again it needs to be emphasized that a routine maintenance inspection and periodic routine repairs appear to be the most effective approaches.

It is evident from the survey responses that bridge engineers have learned from the problems of existing structures regarding the consideration of maintenance needs when constructing new bridges. It is understood that the design of new structures should emphasize durability. The responses indicated both material choices and design philosophies to promote maintenance-free structures.

With regard to details, the most common problem in bridge structures is the detrimental effects of water, whether as an undermining force on bridge foundations, a pressure behind abutments, or as a corrosive catalyst in bridge superstructures. Many of the respondents specified bridge types and details that are more resistant to water-induced problems, with several indicating the use of continuous bridges, jointless bridges, and integral abutments as choices to minimize future bridge maintenance. In scour-prone locations there are several approaches. The first is the use of riprap protection for footings sometimes in conjunction with geotextile reinforcing. Additionally, there is a trend toward providing large hydraulic openings so as to minimize the potential for future scour problems. Where piers are required, the use of pile foundations is recommended as are pile bents; however, where possible, the hydraulic span should be maximized and the piers located out of the main channel.

Regarding superstructure choices, the use of weathering steels was frequently mentioned and, in several instances, the use of galvanized steel was also reported. Both of these steels, when used appropriately, result in largely maintenance-free structures as the problems associated with painting are eliminated. Also mentioned is the use of precast concrete components. Several responses indicated the replacement of older bridges with pipe or box culvert structures, recognizing the very low maintenance requirements of such structures. Virtually all of the concrete bridge deck responses recommended the use of increased cover, high-quality concretes, and corrosion-resistant reinforcing. For timber decks, proper pressure treatment, continued maintenance—specifically with overlays—and protection of the timber deck, were emphasized. The replacement of stringer bridges with transverse timber decks with longitudinal timber slab bridges was mentioned as an effective long-term maintenance solution, as was the replacement of timber-stringer bridges with timber slab spans. Other respondents reported on the replacement of timber structures with concrete and/or steel structures, thus indicating that there are various potential solutions, none of which is always the choice for a given site or owner.

BRIDGE LOAD RATING

An important consideration for highway network managers and bridge engineers is the presence of posted bridges on the system. Posted bridges are those, based on an engineering evaluation, incapable of carrying specified design loads. Posted bridges represent both a potential safety and liability hazard on the system, but may also have significant economic impacts for a region, especially in largely rural regions where reasonable alternate routes are limited or not available. A posted bridge in a critical location may result in significant detours, affecting productivity, or in some instances may render a business inoperable, because its transportation lifeline has been severed. Bridge posting is a function of the procedure agencies use for bridge rating and evaluation. A load rating has a direct effect on the need for rehabilitation and/or strengthening of a bridge. Achieving the most accurate load rating of a given bridge is always desirable, because it may eliminate the need to rehabilitate and/or strengthen a bridge. In recent years, it has become common knowledge that the most accurate method of rating a bridge is to use field load testing, as described in the next section.

Load Testing for Rating

Bridges have been tested for many years. This testing has typically been undertaken to give bridge engineers confidence in their overall design or to study the behavior of specific design details. In the past 10 years there has been an increased interest in using bridge testing for load rating purposes. Unfortunately, there was no established methodology for using field test results in rating calculations. NCHRP Project 12-28(13)A developed an initial guide for bridge rating through nondestructive load testing (Lichtenstein 1993). The general goal of this project was to develop rational methodologies for using field data to study the actual performance of bridges for the purposes of load rating. In some instances, this technique indicates that bridges thought to have low load capacity do actually have sufficient capacity to warrant the removal of load restrictions (i.e., posting).

The final report from this study, *Bridge Rating Through Nondestructive Load Testing*, describes the how, what, why, and when load tests should be performed. Of principal note for bridge owners is the discussion on the intent of load tests and when and when not to perform a load test.

Differences between diagnostic and proof load tests are presented with a discussion of the situations when each should be used. The numerous factors that may have an influence on a load rating and can be investigated through a load test are also summarized. These factors include

- Unintended composite action;
- Load distribution effects;
- Participation of parapets, railings, curbs, and utilities;
- Material property differences;
- Unintended continuity;
- Participation of secondary members;
- Effects of skew;
- Effects of deterioration and damage;
- Load carried by deck; and
- Untended arching action because of frozen bearings.

The author even indicated which of these factors are of primary and secondary concern for various bridge types. This information is particularly useful in establishing an instrumentation plan.

The manual summarizes the complete procedure for incorporating nondestructive testing in bridge rating, including a discussion on how to plan and execute a field load test. In addition, a presentation of typical sensors and data acquisition equipment gives the reader basic information on what is needed to complete a test. The use of field collected data is discussed extensively, with information on processing, reviewing, and using the data in a load rating calculation. The procedure for calculating a rating and the required adjustment factors are thoroughly documented.

Bridge Owners Survey Results: Bridge Load Rating

Bridge owners were asked to comment on their method of bridge rating. As expected, the vast majority of agencies surveyed use the traditional AASHTO *Manual for Condition Evaluation of Bridges* to rate existing bridges (see Figure 9). When queried as to the use of other techniques,

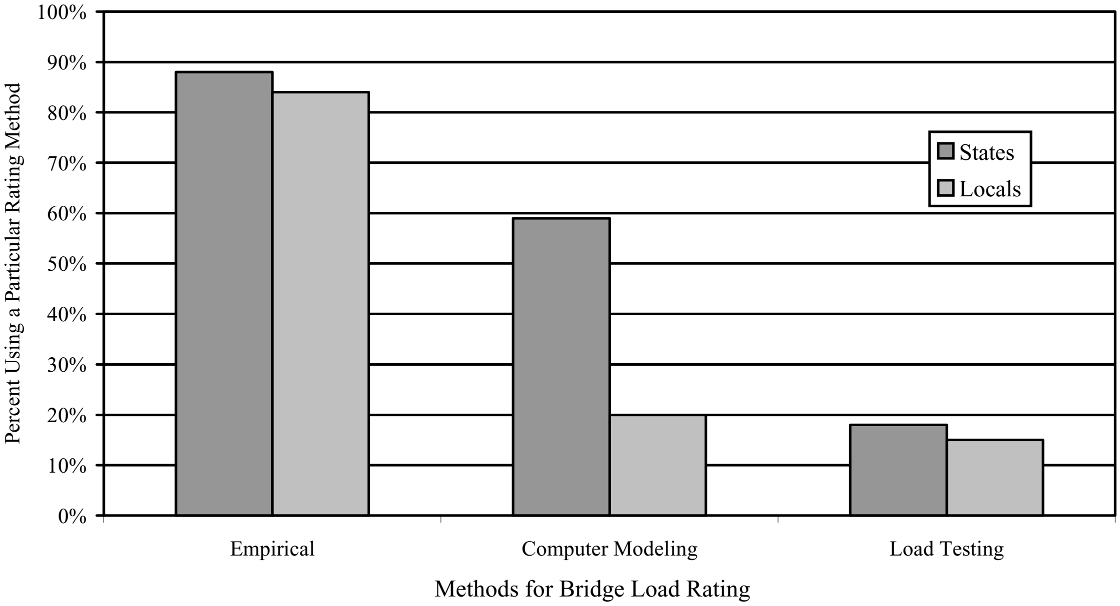


FIGURE 9 State and local agency experience with bridge rating.

such as computer modeling or load testing, the percentage of state or local agencies using either of these approaches decreases significantly. When questioned about their use of computer modeling, 59% of state and 20% of local agency respondents reported the use of computer modeling for bridge rating purposes. Another item of interest was the use of bridge load testing as a tool for evaluating existing bridges—18% of state and 15% of local agencies indicated this use of bridge load testing. Testing was used primarily in situations where a structure could not be rated otherwise or by lack of confidence in empirical results. Examples cited included the testing of stone arches, railroad car bridges, and steel trusses where the rating is either unavailable analytically or is suspect. Additional areas where load testing was used were to avoid replacement of a structure, remove load posting, validate a computer model, and in the analysis of a covered timber bridge. The respondent for the covered timber bridge indicated that perceived testing was a good value for the investment, whereas the respondent discussing the use of load testing on railroad flatcar bridges perceived the cost of testing to be high.

Bridge Owners Survey Results: Bridge Posting

Bridge posting represents a potential safety and liability hazard with economic impacts. Bridge owners were queried as to their methodology for determining when a bridge needs to be posted and what vehicles are used to rate the bridge and determine the posting limit (see Appendix A, Survey Question SD-3).

In general, for both state and local agency respondents, the process used to determine the need for posting and the vehicle loads used vary from agency to agency. Both allowable stress and load factor methods are reported as being used. None of the respondents indicated the use of the newly adopted Load and Resistance Factor Rating method of analysis.

The process for posting will be addressed first. Several approaches were reported, with some of the respondents indicating that a bridge is considered for posting if the inventory rating factor for live load, the rating that relates to the day-to-day service of the bridge, is less than 1.0. Others use the operating rating, the infrequent overload, as the criteria for posting. One state reported using an average of the inventory and operating rating factors, compared to 1.0, as the screening tool for posting. In addition to the strict numerical data that is used to post a bridge, some states reported on the existence of a "committee" of engineers that assesses the data and uses the rating calculations with additional data to decide whether or not to post. For local agency responses the criteria are similar; however, several respondents reported that they do not make the posting determination themselves, rather, consultants or state DOTs, acting on behalf of the local agency, make the recommendation/decision to post the bridge.

Concerning the rating vehicles and those used for posting there is again a significant variation. In addition to state-specific legal loads, the common sources reported are the AASHTO standard, H and HS class loadings, as well as the specific rating vehicles in the *Manual for Condition Evaluation of Bridges*, the Type 3, 3S2, and 3-3 vehicles. Several responses mentioned the use of posting signs depicting axle configurations and allowable gross vehicle weights and others noted that only an allowable gross vehicle weight is stated without regard to axle spacing or number.

STRENGTHENING AND REHABILITATION

If a load rating determines that a bridge cannot safely carry the expected live loads, it is possible to strengthen the bridge. The live-load capacity of various types of bridges can be increased by using different methods such as adding members, adding supports, reducing dead load, providing continuity, providing composite action, applying external post-tensioning, increasing member cross section, modifying load paths, and adding lateral supports or stiffeners. Some methods have been widely used, but others are new and have not been fully developed.

All strengthening procedures presented in this section apply to the bridge superstructure. Although bridge span length is not a limiting factor in the various strengthening procedures presented, most techniques apply to short- to medium-span bridges. Other than a summary of the substructure rehabilitation information presented in the NACE review section, no information is included on the strengthening of existing foundations because such information is dependent on soil type and conditions, type of foundation, and forces involved.

The techniques used for strengthening, stiffening, and repairing bridges tend to be interrelated so that, for example, the stiffening of a structural member of a bridge will normally result in its also being strengthened. A description of maintenance, rehabilitation repair, stiffening, and strengthening was provided earlier in this chapter to clarify their discussion in this report.

In recent years, the FHWA and the NCHRP have sponsored several studies on bridge repair, rehabilitation, and retrofitting. Inasmuch as some of these procedures also increase the strength of a given bridge, the final reports on these investigations are excellent references. These references, plus the strengthening guidelines presented in this section, will provide information an engineer can use to resolve the majority of bridge strengthening problems. The FHWA and NCHRP final reports related to this investigation are Berger 1978; Fisher et al. 1979; Shanafelt and Horn 1980, 1984, 1985; University of Virginia Civil Engineering Department 1980; Mishler and Leis 1981; Applied Technology Council 1983; Sabnis 1983; Sprinkle 1985; Klaiber et al. 1987; Dorton and Reel 1997.

Four of these references (Berger 1978; University of Virginia Civil Engineering Department 1980; Klaiber et al. 1987; and Dortan and Reel 1997) are of specific interest in strengthening work. Although not discussed in this section, the live-load capacity of a given bridge can often be evaluated more accurately by using more refined analysis procedures. If normal analytical methods indicate that strengthening is required, frequently more sophisticated analytical methods (such as finite-element analysis) may result in increased live-load capacities, therefore eliminating the need to strengthen or significantly decreasing the amount of strengthening required.

As discussed previously, data obtained in the load testing of bridges frequently reveals live-load capacities that are considerably larger than would be determined using analytical procedures. Load testing of bridges makes it possible to take into account several contributions (such as end restraint in simple spans and structural contributions of guardrails) that cannot be included analytically. In the past few years, several states and counties have started using load testing to establish the live-load capacities of their bridges. Most states also have some type of Bridge Management System (BMS). However, it would appear that very few states are using their BMS to make bridge strengthening decisions. At the present time, there is insufficient base line data [first cost, life-cycle costs (LCC), cost of various strengthening procedures, etc.] to make strengthening or replacement decisions.

Examination of NBI bridge records indicates that the bridge types with the greatest potential for strengthening are steel stringer, timber stringer, and steel thru truss. If rehabilitation and strengthening cannot be used to extend their useful lives, many of these bridges will require replacement in the near future. Other bridge types for which there also is potential for strengthening are concrete slab, concrete tee, concrete stringer, steel-girder floor-beam, and concrete-deck arch. In this section, information is provided on the more commonly used strengthening procedures, as well as a few of the new procedures that are currently being researched.

Bridge Rehabilitation

In conjunction with their publication concerning bridge maintenance on local roads, the NACE published *Bridge Rehabilitation on Local Roads* (1995), a guide that presents effective bridge rehabilitation methods applicable to bridge types commonly found on the local road system. The guide is divided into sections related to planning activities, bridge decks and railings, trusses, beams and girders, expansion joints and bearings, substructures, waterways, and support activities. The guide has been developed in response to the large number of bridges regarded as deficient on the local road system and considers the budgetary constraints local agencies face when addressing bridge rehabilitation needs.

Bridge rehabilitation is only part of a broad bridge administration policy that includes bridge inspection, maintenance, rehabilitation, and long-range planning. Bridge rehabilitation generally begins with a routine bridge inspection to catalog existing conditions. Following inspection, an analysis of the inspection data identifies the required rehabilitation work and considers the costs of the needed improvements for purposes of programming. A consideration of the impacts of rehabilitation should also be made with regard to required permits, needs for detours, engineering and contractual documents, and workzone safety.

Bridge Inspection

An important part of bridge rehabilitation is the proper inspection of bridge structures. This is required for purposes of federal reporting using the standard Structural Inventory and Appraisal (SI&A) form. Depending on the condition rating of the structure and its geometric features, a bridge may be classified as adequate, structurally deficient, or functionally obsolete. Based again on the condition ratings reported on the SI&A sheets, a sufficiency rating is computed for each bridge as a measure of the bridges' structural and functional condition. A sufficiency rating of 100 indicates complete sufficiency (i.e., a new bridge), whereas a sufficiency rating of 0 indicates a completely insufficient bridge. Because of the very extensive nature of the NACE rehabilitation guide, only brief descriptions of the key items will be presented in this synthesis. A complete copy of *Bridge Rehabilitation on Local Roads* is available from the NACE.

Bridge Deck Rehabilitation

The most common form of deterioration in bridge structures is in the bridge decks. It is also the most objectionable to the traveling public because of its impact on ride quality. For these reasons, it is a critical rehabilitation activity. Bridge decks are addressed with respect to proper inspection and appropriate means of rehabilitation. Although timber and steel grid decks are mentioned, most coverage is on concrete decks, because they are the most prevalent.

Concrete Decks Chloride contamination is the most common cause of deterioration of concrete decks. Once chlorides reach the reinforcing steel, especially in older noncoated bridge decks, the reinforcing steel begins to corrode resulting in spalling, more extensive cracking, and an acceleration of deck deterioration. To determine the appropriate rehabilitation of concrete bridge decks, an adequate deck condition survey must be performed. The condition survey should determine the amount of bridge deck spalling and surface deterioration, whereas a more complete assessment would also involve a determination of bridge deck delamination, half-cell potential, and chloride content sampling. Following the survey of the bridge deck, its condition is rated on a scale of 0 to 9 for purposes of recording on an SI&A sheet. Bridge decks rated less than 4 (extensive deterioration) result in the classification of the bridge as structurally deficient.

To prevent bridge deck deterioration from occurring, or at least delay its onset because total prevention is unlikely, various treatments may be used, including the application of penetrating concrete sealers and the use of waterproofing membranes. Neither of these solutions is permanent because they themselves are subject to wear and deterioration. Additionally, they are only appropriate for bridge decks with minor deterioration and no indications of chloride penetration.

For more extensive deterioration, additional rehabilitation measures are required above and beyond those used for decks in fairly good condition. When deck deterioration is isolated to discrete areas, deck patching is frequently warranted, with either partial or full-depth patches being used as appropriate. In some instances deck patching may actually compound the problem. Patching typically only repairs the deteriorated concrete and may not be effective in arresting deterioration of the reinforcing steel or remove chlorides from surrounding concrete. For decks where the riding surface is more uniformly deteriorated or where additional concrete cover is desired deck overlays may be used. These overlays are typically constructed with either dense portland cement concrete or latex-modified concrete. In addition to normal deck overlays that bond directly to the old deck, overlays may also be constructed with an intermediate membrane between the old and new deck courses. Before application of the membrane, delaminations, active corrosion areas, and chloride-contaminated areas should be repaired so that they are not trapped under the membrane and wearing course.

For instances of extensive deck deterioration, the most feasible and prudent alternative may be a complete deck replacement. Various options exist for replacing deteriorated concrete decks with new concrete decks. In a number of cases, there are extensive deck deterioration and low superstructure ratings. These issues may be addressed simultaneously by removing the deteriorated noncomposite deck and replacing it with a new composite deck. The new deck may be placed as either a cast-in-place (CIP) deck, the traditional method, or with precast concrete panels with blockouts to allow for grouting to the shear connectors. Various schematic options for precast deck panel replacements are presented in the NACE guide.

Timber Decks Although not as common as concrete decks, there are still a large number of timber decks on highways, especially on low-volume and off-system road networks. They are a viable deck system, especially when the current high-quality pressure-treated lumbers (available in glue-laminated, spike-laminated, or stress-laminated panels) are used in bridge construction. Timber bridge decks may be used on short-span timber bridges or as decks on short- to medium-span steel-stringer bridges. The U.S. Department of Agriculture's (USDA) Forest Products Laboratory (FPL) publishes an extensive amount of literature on the design, construction, and performance of timber bridge decks. The literature covers species selection, design capacities, and construction details, and includes case histories of in-place performance.

Steel Decks In addition to timber decks, steel grid decks, whether composed of open-steel decks or partially filled grids, are frequently used. In Ohio, galvanizing steel grid decks has been shown to increase the deck life by 15 or more years. The open-steel grids come in various gages and depths providing various spanning capabilities, but have the downside of exposing the bridge superstructure directly to the effects of deicing chemicals, snow, rain, and other contaminants. They are also susceptible to fatigue. A refinement of the open deck system, which still results in lightweight deck systems, is the partially filled deck, which is filled with several inches of concrete. This system is a more durable option and worth considering for deck replacements in which both durability and dead-load reduction are desired. Finally, a low-cost noncomposite bridge deck type is one that employs stay-in-place metal deck forms similar to those used to build concrete decks; however, in this application, the forms are filled with bituminous material. Because of the porous nature of the bituminous paving material, corrosion of the deck pans is a concern and should be considered and monitored accordingly.

Truss Rehabilitation

Truss bridges are still present on the local road system. Nationally, according to NBI data published in August 2000, approximately 17,500 truss bridges remain in service. Of these trusses, 801 are deck trusses and the remaining 16,735 thru trusses. For the deck trusses, 40% are considered structurally deficient and an additional 20% are functionally obsolete. The statistics for thru trusses indicate that almost 64% are structurally deficient and an additional 17% are functionally obsolete. These bridges are generally old, narrow, composed of riveted steel, and carry low volumes of traffic, although not necessarily low loads in all cases. Because of the large numbers of these bridges on local roads, an effective means of rehabilitation is still required. An additional complication when considering rehabilitation of old truss bridges is their potential historic status.

Of critical importance in evaluating truss bridges is that they are generally considered to be nonredundant structures as a result of there only being two main trusses. Many of the truss members are fracture critical, indicating that failure of any of these key members would theoretically result in the bridge's collapse. Old trusses may be composed of multiple eyebars and pin connected members, which are especially vulnerable to deterioration, fatigue, and fracture. These members can be difficult to inspect and repair. A careful consideration of the existing strength as well as material sampling is important for an accurate evaluation of some older trusses.

Floor System The floor system of a truss is the combination of transverse floor beams, supported at truss panel point locations, and the longitudinal stringers that typically rest on the top flanges of the floor beams and support the bridge deck. The typical cause of deterioration in the floor system is the leakage of water through the decks and onto the members of the floor system. Additionally, the ends of floor beams at the connection to the truss and end floor beams under expansion joints are particularly vulnerable because of their more direct exposure to the elements. In rehabilitation, replacement of deteriorated stringers and floor beams, failed decks, and drainage systems is a common solution. If the deterioration is only localized and deemed repairable, the addition of cover plates to stringers and/or floor beams is a common solution.

Truss Elements The rehabilitation of truss elements is addressed here as it relates to web vertical and diagonal members, top and bottom chords, and truss panel point connections. Deteriorated truss members may be strengthened with the addition of cover plate material, by the addition of longitudinal bars to the cross section, and by post-tension strengthening of the deficient tension members, among other options. Truss members that have been bent by vehicle impact may be heat straightened. Thru trusses with deficient bottom chord members may be strengthened either by the addition of cover plates or supplemental reinforcing material along the bottom chords. They also can be strengthened by the application of an external truss such as a single-post king post truss or multiple-post queen post trusses. The NACE guide (*Bridge Rehabilitation on Local Roads* 1995) gives various illustrations and recommendations for the repair of damaged truss members.

Beam and Girder Rehabilitation

Various methods are available for beam and girder rehabilitation, several of which are detailed in the NACE guide. Because beams and girders are the primary components of multi-beam bridges and as components in girder-floor beam-stringer bridges and truss bridges, their repair is particularly important and common.

Steel Beams and Girders Both steel beams and girders are common, representing approximately one-third of the nation's bridge population. They are subject to various forms of deterioration, including overstress, damage, corrosion, and fatigue and fracture. They may be repaired by various methods, including the addition of bolted cover plates or supplemental members or by welding. Field welding should only be performed with care; it should never be performed on fracture critical members or members where fatigue is a concern. Beam end corrosion under failed expansion joint drainage systems is a particular concern that typically requires remedial action owing to local beam failure.

A procedure for rehabilitating steel bridges that has the possibility of reducing future maintenance costs and improving the bridge rating is the conversion of multiple simple spans into a continuous bridge. This is accomplished by removing the expansion joints at piers and splicing the stringer ends with web and flange splice plates and adding reinforcement to the created negative moment region in the deck. This procedure results in the bridge behaving as simply supported for noncomposite dead load and continuous for live load, much the same as the way modern prestressed concrete bridges are constructed. Another method for increasing the capacity of deficient steel bridges is through addition of an intermediate bent, or span shortening, to help reduce live-load stresses. This modification is difficult to achieve for roadway grade separation structures because the helper bent would likely be an impediment to traffic below. However, it may be possible to employ such a technique on small stream or ditch crossings. Again, similar to truss bridge strengthening, steel stringers may be rehabilitated by external post-tensioning or by the addition of external king post trusses.

Concrete Beams The most common form of deterioration to concrete structures is the result of the deterioration of the underlying reinforcing steel. For reinforced concrete beams, hairline cracks are not uncommon; however, for prestressed concrete beams there should be no evidence of cracking. Cracking of prestressed concrete may be indicative of a more serious problem, such as the loss of prestressing, and should be investigated more thoroughly. Similar to steel beams, concrete beams are predisposed to deterioration at the beam ends where they are subjected to leakage from expansion joints and failed drainage systems. Such deterioration will result in steel deterioration and loss of section of the beam ends. A possible solution includes the removal of damaged concrete and the epoxy doweling of supplemental reinforcing into the beam, after which the section is restored with a durable concrete or grout. Another solution for failed beam ends is to extend the supports out into the span. This might involve the building of corbels on the front face of an abutment to support a still sound portion of the beam or could include construction of similar brackets and corbels on the faces of bridge pier caps. The NACE guide has several schematic illustrations of pier and abutment modifications for support relocation.

Timber Beams Timber beam rehabilitation is addressed in the NACE guide. Although timber bridges represent only 6% of the nation's bridges, the vast majority of these structures are located on local roads. According to the NACE guide, timber bridge beams can be rehabilitated as long as their original load carrying capacity has not been reduced by more than 50%. Rehabilitation options may include partial replacement of damaged sections with new material being spliced in as a repair. Timber stringers in multi-beam bridges are typically damaged on their top surface owing to moisture penetration from the deck. This also results in the loosening of the connection between the deck and stringers. Engineers are strongly cautioned against flipping damaged stringers over so that the "good side" is at the top. By placing the moisture and nail damaged portion of the stringer on the bottom of the beam, the zone of tension, the capacity of the beam has been significantly compromised. Instead of imprudent repairs such as beam flipping, more advisable techniques include the addition of side helper beams of timber or steel, the addition of bottom steel cover plates, and epoxy repair of damaged timbers. If only a few defective stringers in a span need to be replaced, this can be done from above by localized deck removal. As an alternative, stringers may be replaced from below by slightly jacking the deck up in the vicinity of the damaged stringer, sawing it for removal, and slightly beveling the corners of a new stringer along with cutting a shallow wedge on the top flange of one end so that it may be placed under the deck.

Joint and Bearing Rehabilitation

Bridge Joints As has been mentioned, leakage and failure of joints are detrimental to the underlying superstructure. However, failure of the joints themselves is problematic. Common problems with expansion joints include the likelihood that they may become fouled with debris resulting in problems with expansion and contraction, which will cause subsequent damage to abutment backwalls and bridge decks. In short bridges, it is not uncommon to have small open joints at the expansion locations with armored edges to protect the exposed concrete. These edges typically are damaged anyway resulting in the required replacement of the armoring angles. This can be accomplished by removal of a short section of concrete, attachment of a bent angle welded to both the longitudinal reinforcing and the armor angle, and recasting of the deck and approach concrete in the vicinity of the repair. As a repair for sliding plate joints, which typically leak or become frozen from deterioration, an effective option is to cut off the sliding plate at the face of the angle to which it is attached and fill in the gap with a compression seal or strip seal expansion joint. Another option is the use of glands that do not require steel extrusion angles. These glands are glued to exposed steel or concrete faces and are a viable retrofit for previous failed joints. A further option is the use of elastomeric concrete at both sides of the expansion joint with a strip seal bridge over the joint. However, all of these repair and rehabilitation solutions are still prone to potential leaks and can be expensive. For these reasons, the complete elimination of joints is encouraged when feasible.

Bridge Bearings Bridge bearings have the dual function of providing vertical support as well as allowing for longitudinal movement or restraint. Older bearings such as rollers, pintle bearings, rockers, pin bearings, fixed shoes, roller nests, etc., are all composed of multiple steel pieces whose strength and movement capabilities must be accessed. Bridge bearing rehabilitation typically involves providing some means for bridge jacking so that bearings can be replaced, repaired, realigned, or otherwise rehabilitated. Bridge bearing rehabilitation may also involve bearing seat repairs. Older bridge bearings that rely on multiple parts moving relative to each other to function properly need to be properly cleaned, lubricated, and aligned. In many cases, especially in short- and medium-span bridges where neither the vertical loads nor expected movements are significant, problematic expansion bearings may be effectively replaced with low-cost and low-maintenance elastomeric bearings.

Bridge Substructure Rehabilitation

Bridge substructures are a critical element of a bridge in that they provide support for the entire structure. Although they are generally lower maintenance than the bridge superstructure components, their repair and rehabilitation, when required, may be expensive, time consuming, and much more difficult to accomplish than bridge superstructure repairs.

Abutments and Backwalls Bridge abutments and backwalls serve the purpose of supporting the end of the bridge, retaining the approach fills, and resisting the effects of longitudinal and transverse forces imposed on the bridge superstructure. They are subjected to forces from the bridge superstructure as well as from the retained earth and water pressures behind the abutment stem. Typical surface damage such as spalls and cracking can be effectively repaired as long as they have been stabilized. Repairs to damage that is known to be progressing are not likely to be effective. Typical surface repairs include concrete patching and epoxy or latex crack injection. For more extensive deterioration of bridge abutments, a concrete jacket may be placed over the entire height of the abutment from the bridge seat down to the top of the footing. This concrete should be doweled to the existing structure and placed with the aid of a bonding agent to an intentionally roughed surface. For stone abutments, maintenance and rehabilitation generally involves the maintenance of mortar joints. For timber abutments, routine member replacement is the likely rehabilitation option because timbers, even treated, are prone to decay. Selective replacement of damaged members and the addition of helper elements are frequently employed.

Piers Bridge piers are the intermediate supports for multi-span structures. They may be situated on land or within the limits of a waterway. Repairs to bridge piers can be at the bridge cap level as a result of leaking joints, to the columns or wall stems because of vehicular impact damage, or to the footings owing to loss of support from undermining. Footings with deficient capacity can be widened or thickened. The new concrete must be doweled to the existing, and new piles may be added if necessary. Footing scour results in the loss of soil or erodible rock from underneath a bridge pier. This results in either a loss of capacity for spread footings or the creation of potentially problematic unbraced lengths for pile foundations. Solutions include placement of tremie concrete seals under the pier footing or hand placement of grout bags or bags of cement. These bags constitute the formwork for the grout underpinning of the bridge footing. Following underpinning, the footing is protected with a blanket of stone riprap.

Piles There are cases where bridge piles themselves require rehabilitation because of environmental effects. For steel or timber piles, there is the possibility of splicing over the damaged area with retrofit material to replace lost capacity or, in some instances, complete removal of a length of pile and replacement with a similar material. Bearing piles that also form part of a pile bent are frequently damaged by vessels, debris, and ice, all of which may require rehabilitation or replacement. Typically, in replacement situations, the new piles are driven through an opening in the deck of the bridge into the foundation material. The new piles can then be integrated into the bent as a whole, thus replacing any lost capacity.

Waterway Rehabilitation

Rehabilitation of waterways in the vicinity of bridges is sometimes required to eliminate bridge maintenance problems. In addition to bridge scour problems, which are common for waterway crossings, there are also the challenges of meandering stream channels that may encroach upon previously "protected" footings and the problem of general streambed lowering. Reasonable efforts should be taken to maximize the hydraulic opening in the vicinity of a bridge. Additionally, the stream cross section should not be substantially modified in the bridge area, as this can lead to varied flow characteristics. If it is determined that stone riprap is required, predicted velocities from a hydraulic analysis should be completed to size the stone accordingly. The stone should be placed beginning below the level of the natural streambed and should extend up the sides of the footing and in many cases cover it for the appropriate degree of protection. An expansion of the isolated footing protection scheme is the use of a stone blanket or apron across much of the stream and in many cases extending up onto the banks, which is used where there is general degradation of the stream cross section as opposed to isolated scour. If the source of the problem is a poor stream alignment, changes in the flow pattern of the stream may be required through use of flow-altering hydraulic structures such as spur dikes, wing dikes, check dams, jack fields, and flow retarders. These measures individually or in combination are used to slow the flow near stream banks and hence reduce the tendency for erosion or are used to reduce the flow velocity generally across the stream thus reducing the likelihood for footing scour. These devices require temporary and permanent waterway impacts and require environmental reviews and permits as encroachments.

Bridge Strengthening

Several of the topics presented in this section were previously briefly reviewed in the NACE publication, *Bridge Rehabilitation on Local Roads* (1995). In this section, additional details on strengthening procedures as well as several case studies are presented.

Lightweight Decks

One of the more fundamental approaches to increasing the live-load capacity of a bridge is to reduce its dead load. Significant reductions in dead load can be obtained by removing an existing heavier concrete deck and replacing it with a lighter weight deck. In some cases, further reduction in dead load can be obtained by replacing the existing guardrail system with a lighter weight guardrail. The concept of strengthening by dead-load reduction has been used primarily on steel structures, including the following types of bridges: steel stringer and multibeam, steel girder and floor beam, steel truss, steel arch, and steel suspension; however, this technique could also be used on bridges constructed of other materials.

Lightweight deck replacement is a feasible strengthening technique for bridges with structurally inadequate but sound steel stringers or floor beams. However, if the existing deck is not in need of replacement or extensive repair, lightweight deck replacement would not be economically feasible.

Lightweight deck replacement can be used conveniently in conjunction with other strengthening techniques. After an existing deck has been removed, structural members can readily be strengthened, added, or replaced. Composite action, which is possible with some lightweight deck types, can further increase the live-load carrying capacity of a deficient bridge.

Open-Grid Steel Decks

Open-grid steel decks are lightweight, typically weighing 720 to 1,200 Pa (15 to 25 psf) for spans of up to 1.52 m (5 ft). Heavier decks, capable of spanning up to 2.74 m (9 ft), are also possible; the percent increase in live-load capacity is maximized with the use of an open-grid steel deck. Open-grid decks are often not perceived favorably by the general public because of the poor skid resistance, poor riding quality, and increased tire noise.

Concrete-Filled Steel Grid Decks

Concrete-filled steel grid decks weigh substantially more than, but have several advantages over, the open-grid steel decks, including increased strength, improved skid resistance, and better riding quality. The steel grids can be either half or completely filled with concrete. A 130-mm (5-in.)-thick, half-filled steel grid weighs 2.20 to 2.44 kPa (46 to 51 psf), less than one-half the weight of a reinforced concrete deck of comparable strength. Typical weights for 130-mm (5-in.)-thick steel grid decks, filled to full depth with concrete, range from 3.64 to 3.88 kPa (76 to 81 psf). Reduction in the dead weight resulting from concrete-filled steel grid deck replacement alone only slightly improves the live-load capacity; however, the capacity can be further improved by providing composite action between the deck and stringers.

Exodermic Decks

An Exodermic deck is a prefabricated, proprietary, modular deck system that has been marketed by a major steel grid deck manufacturer. The first application of an Exodermic deck was in 1984 in New Jersey (DePhillips 1985). The bridge deck system consists of a thin upper layer [76 mm (3 in.) minimum] of prefabricated concrete joined to a lower layer of steel grating. The deck weighs from 1.92 to 2.87 kPa (40 to 60 psf) and is capable of spanning up to 4.88 m (16 ft).

The Exodermic deck and half-filled steel grid deck have the highest percentage increase in live-load capacity among the lightweight deck types with a concrete surface. An Exodermic deck can be quickly installed as a prefabricated modular deck system. Because the panels are fabricated in a controlled environment, quality control is easier to maintain and panel fabrication is independent of the weather or season.

Laminated Timber Decks

Laminated timber decks consist of vertically laminated 2-in. (51-mm) (nominal) dimension lumber. The laminates are bonded together with a structural adhesive to form panels that are approximately 1.22 m (48 in.) wide. The panels are typically oriented transverse to the supporting structure of the bridge. In the field, adjacent panels are secured to each other with steel dowels or stiffener beams to allow for load transfer and to provide continuity between the panels.

A steel–wood composite deck for longitudinally oriented laminates was developed by Bakht and Tharmabala (1985). Individual laminates are transversely post-tensioned in the manner developed by Csagoly and Taylor (1980). The use of shear connectors provides partial composite action between the deck and stringers. Because the deck is placed longitudinally, diaphragms mounted flush with the stringers may be required for support. Design of this type of timber deck is presented by Taylor et al. (1982) and the Canadian Ministry of Transportation and Communications (1983a,b).

The laminated timber decks used for lightweight deck replacement typically range in depth from 79 to 171 mm (3.125 to 6.75) and in weight from 500 to 1,075 Pa (10.4 to 22.5 psf). A bituminous wearing surface is recommended.

Wood is a replenishable resource that offers several advantages: ease of fabrication and erection, high strength-to-weight ratio, and immunity to deicing chemicals. The most common problem associated with wood as a structural material is its susceptibility to decay; however, with the use of modern preservative pressure treatments, the expected service life of timber decks can be extended to 50 years or more.

Lightweight Concrete Decks

Structural lightweight concrete, concrete with a unit weight of 1840 kg/m^3 (115 pcf) or less, can be used to strengthen steel bridges that have normal-weight, noncomposite concrete decks. Special design considerations are necessary for lightweight concrete; its modulus of elasticity and shear strength are less than that of normal-weight concrete, whereas its creep effects are greater (Mackie 1985). The durability of lightweight concrete can be a problem in some applications.

Lightweight concrete for deck replacement can be either CIP or installed in the form of precast panels. A CIP lightweight concrete deck can easily be made to act compositely with the stringers. Lightweight precast panels, fabricated with either mild steel reinforcement or transverse prestressing, have been used in deck replacement projects to help to minimize erection time and resulting interruptions to traffic. Precast panels require careful installation to prevent water leakage and cracking at the panel joints.

Other Deck Systems

Steel orthotropic plate decks are an alternative for lightweight deck replacements that generally have been designed on a case-by-case basis, without a high degree of standardization. Orthotropic steel decks are heavier than aluminum orthotropic decks and usually have weights in the 2.15 to 6.22 kPa (45 to 130 psf) range. Because aluminum and steel orthotropic deck systems are used primarily on long-span steel bridges, when a reduction in the dead load is more significant, no additional information will be presented on this type of deck system in this synthesis.

Lightweight Deck Case Studies

Steel Grid Decks The West Virginia Department of Highways was one of the first transportation agencies to develop a statewide bridge rehabilitation plan using the open-grid steel deck ("Steel Grids Rejuvenate Old Bridges" 1974). By 1974, 25 bridges had been renovated to meet or exceed AASHTO requirements. Deteriorated concrete decks were replaced with lightweight, honeycombed steel grid decks. The new bridge floors are expected to have a 50-year life and require minimal maintenance.

In 1981, the West Virginia Department of Highways increased the live-load limit on a 546.8-m (1,794-ft)-long bridge over the Ohio River from 26.69 kN (3 tons) to 115.65 kN (13 tons) by replacing the existing reinforced concrete deck with an open-steel grid deck ("CAWV Members Join Forces . . ." 1982; "Lightweight Decking Rehabs . . ." 1982). The existing deck was removed and the new deck installed in sections, allowing one-half of the bridge to be left open for use by workers and, if needed, emergency vehicles.

The strengthening of the 76.2-m (250-ft)-long Old York Road Bridge in New Jersey in the early 1980s combined deck replacement with the replacement of all of the main framing members and the modernization of the piers and abutments ("The Rehabilitation of the Old York Road Bridge" 1983). The posted 89 kN (10 ton) load limit was increased to 320 kN (36 tons) and the bridge was widened from 5.49 m (18 ft) to 7.92 m (26 ft).

Exodermic Decks The first installation of an Exodermic deck was in 1984 on the 1340-m (4,400-ft)-long Driscoll Bridge, spanning the Raritan River in Middlesex County, New Jersey (DePhillips 1985). The deck, weighing

2.54 kPa (53 psf), consisted of a 76 mm (3 in.) upper layer of prefabricated reinforced concrete joined to a lower layer of steel grating.

An Exodermic deck was also specified for the deck replacement on a four-span bridge that overpasses the New York State Thruway (Campisi 1986). The bridge was closed to traffic during deck removal and replacement. Once the existing deck was removed, it was estimated that approximately 697 m^2 (7,500 ft^2) of Exodermic deck was installed in three working days.

Lightweight Concrete Decks Lightweight concrete was used as early as 1922 for new bridge construction in the United States. Over the years, concrete made with good lightweight aggregate has generally performed satisfactorily; however, some problems have been experienced related to the durability of the concrete. The Louisiana DOT experienced several deck failures on bridges built with lightweight concrete in the late 1950s and early 1960s. The deck failures have typically occurred on bridges with high traffic counts and have been characterized by the sudden and unexpected collapse of sections of the deck.

Lightweight concrete decks can either be CIP or factory precast. Examples of the use of lightweight concrete for deck replacement follow.

CIP Concrete New York State authorities used lightweight concrete to replace the deck on the north span of the Newburgh–Beacon Bridge across the Hudson River (Holm 1985). The existing deck was replaced with 165 mm (6.5 in.) of CIP lightweight concrete that was surfaced with a 38 mm (1.5 in.) layer of latex-modified concrete. Use of the lightweight concrete allowed the bridge to be widened from two to three lanes with minimal modifications to the substructure. A significant reduction in the cost of widening the northbound bridge was attributed to the reduction in dead load.

Precast Concrete Panels Precast modular deck construction has been used successfully since 1967 when a joint study, conducted by Purdue University and Indiana State Highway Commission, found precast, prestressed deck elements to be economically and structurally feasible for bridge deck replacement (Ford 1969; Kropp et al. 1975).

Precast panels, made of lightweight concrete [1840 kg/m^3 (115 pcf)], were used to replace and widen the existing concrete deck on the Woodrow Wilson Bridge, located on Interstate 95, south of Washington, D.C. (Greiner Engineering Sciences 1983; Nickerson 1985). The precast panels were transversely prestressed and longitudinally post-tensioned. Special sliding steel-bearing plates were used between the panels and the structural steel to prevent the introduction of unwanted stresses in the superstructure.

Composite Action

Modification of an existing stringer and deck system to a composite system is a common method of increasing the flexural strength of a bridge. The composite action of the stringer and deck not only reduces the live-load stresses but also reduces undesirable deflections and vibrations as a result of the increase in the flexural stiffness from the stringer and deck acting together. This procedure can also be used on bridges that only have partial composite action, because the shear connectors originally provided are inadequate to support today's live loads.

Although numerous devices have been used to provide the required horizontal shear resistance, the most common connection used today is the welded stud. Composite action can effectively be developed between steel stringers and various deck materials, such as normal-weight reinforced concrete (precast or CIP), lightweight reinforced concrete (precast or CIP), laminated timber, and concrete-filled steel grids. Because steel stringers are normally used for the support of all the mentioned decks, they are the only type of superstructure reviewed. The condition of the deck determines how composite action can be obtained between the stringers and an existing concrete deck. If the deck is badly deteriorated, composite action is obtained by removing the existing deck, adding appropriate shear connectors to the stringers, and recasting the deck. This was done in Blue Island, Illinois, on the 457-m (1,500-ft)-long steel plate girder Burr Oak Avenue Viaduct ("Bridge Rebuilt with Composite Design" 1960).

Precast concrete panels can be used to reduce construction time. The panels are made composite by positioning holes formed in the precast concrete directly over the structural steel. Welded studs are then attached through the preformed holes. This procedure was used on an I-80 freeway overpass near Oakland, California (Collabella 1984). Panels 9.1 m (30 ft) to 12.2 m (40 ft) long, with oblong holes 305 mm (12 in.) x 100 mm (4 in.) were used to replace the existing deck. Four studs were welded to the girders through each hole. Composite action was obtained by filling the holes, as well as the gaps between the panels and steel stringers, with fast-curing concrete.

If the concrete deck does not need replacing, composite action can be obtained by coring through the existing concrete deck to the steel superstructure. Appropriate shear connectors are placed in the holes; the desired composite action is then obtained by filling the holes with nonshrink grout. This procedure was used in the reconstruction of the

Pulaski Skyway near the Holland Tunnel linking New Jersey and New York (Collabella 1984).

Improving Strength of Bridge Members

Addition of Steel Cover Plates on Steel Stringers One of the most common procedures used to strengthen existing bridges is the addition of steel cover plates to existing members. Steel cover plates, angles, or other sections may be attached to bridge beams by means of bolts or welds. The additional steel is normally attached to the flanges of existing sections as a means of increasing the section modulus, thereby increasing the flexural capacity of the member. In most cases, the member is jacked up during the strengthening process, relieving dead-load stresses on the existing member. The new cover plate section is then able to accept both live-load and dead-load stresses when the jacks are removed, which ensures that less steel will be required in the cover plates. If the bridge is not jacked up, the cover plate will carry only live-load stresses, and more steel will be required.

The most commonly reported problem encountered with the addition of steel cover plates is fatigue cracking at the toe of the welds at the ends of the cover plates. In a study by Wattar et al. (1985) it was suggested that bolting be used at the cover plate ends. Tests showed that bolting the ends raises the fatigue category of the member and also results in material savings by allowing the plates to be cut off at the theoretical cutoff points.

Materials other than flange cover plates may be added to stringer flanges for strengthening. For example, the Iowa DOT prefers to attach angles to the webs of steel I-beam bridges (either simple supported or continuous spans) with high-strength bolts as a means to reducing flexural live-load stresses in the beams. In some instances, the angles are attached only near the bottom flange. Because the angles are bolted on, problems of fatigue cracking that could occur with welding are eliminated.

Addition of Steel Shapes on Reinforced Concrete Beams One method of increasing the flexural capacity of a reinforced concrete beam is to attach steel cover plates or other steel shapes to the beam's tension face. The plates or shapes are normally attached by bolting, keying, or doweling to develop continuity between the old beam and new material. If the beam is also inadequate in shear, combinations of straps and cover plates may be added to improve both shear and flexural capacity. Because a large percentage of the load in most concrete structures is dead load, for cover plating to be most effective, the structure should be jacked before cover plating to reduce the member's dead-load stresses. The addition of steel cover plates may also require the addition of concrete to the compression face of the member.

A successful method of strengthening reinforced concrete beams has involved the attachment of a steel channel to the stem of a beam. Taylor (1976) performed tests on a beam section using steel channels and found it to be an effective method of strengthening. The channels can also be easily reinforced with welded cover plates if additional strength is required. It should be noted that the bolts are placed above the longitudinal steel so that the stirrups can carry shear forces transmitted by the channels. If additional shear capacity is required, external stirrups could also be installed. It is also recommended that an epoxy resin grout be used between the bolts and concrete. The epoxy resin grout provides greater penetration in the bolt holes, thereby reducing slippage and improving the strength of the composite action.

Addition of External Shear Reinforcement to Concrete, Steel, and Timber Beams The shear strength of reinforced concrete beams or prestressed concrete beams can be improved with the addition of external steel straps, plates, or stirrups. Steel straps are normally wrapped around the member and can be post-tensioned. Post-tensioning allows the new material to equally share both dead and live loads with the old material, resulting in more efficient use of the material added. A disadvantage of adding steel straps is that cutting the deck to apply the straps leaves them exposed on the deck surface and thus difficult to protect.

Timber stringers with inadequate shear capacity can be strengthened by adding steel cover plates. *NCHRP Report 222* (University of Virginia Civil Engineering Department et al. 1980) described a method of repairing damaged timber stringers with inadequate shear capacity. The procedure involves attaching steel plates to the bottom of the beam in the deficient region with draw-up bolts placed on both sides of the beam. Holes are drilled through the top of the deck, and a steel strap is placed at the deck surface and at the connection to the bolts.

Epoxy Injection and Rebar Insertion The Kansas DOT has developed and successfully applied a method for repairing reinforced concrete girder bridges. The bridges had developed shear cracks in the main longitudinal girders (Stratton et al. 1982). The procedure used by the Kansas DOT not only prevented further shear cracking but also significantly increased the shear strength of the repaired girders.

The method involves locating and sealing all of the girder cracks with silicone rubber, marking the girder center line on the deck, locating the transverse deck reinforcement, vacuum drilling 45-degree holes that avoid the deck reinforcement, pumping the holes and cracks full of epoxy, and inserting reinforcing bars into the epoxy-filled holes.

An advantage of using the epoxy repair and rebar insertion method is its wide application to a variety of bridges. Although the Kansas DOT reported using this strengthening method on two-girder, continuous, reinforced concrete bridges, this method can be a practical solution on most types of prestressed concrete beam and reinforced concrete girder bridges that require additional shear strength.

Addition of External Shear Reinforcement Strengthening a concrete bridge member that has a deficient shear capacity can be done by adding external shear reinforcement. The shear reinforcement may consist of steel side plates or steel stirrup reinforcement, a method that has been applied on numerous concrete bridge systems.

A method proposed by Warner (1981) involves adding external stirrups. The stirrups consist of steel rods placed on both sides of the beam section and attached to plates at the top and bottom of the section. In some applications, channels are mounted on both sides at the top of the section to attach the stirrups, which eliminates drilling through the deck to make the connection to a plate.

In a study by Dilger and Ghali (1984), external shear reinforcement was used to repair webs of prestressed concrete bridges. Although the measures used were intended to restore the deficient members to their original flexural capacity, the techniques applied could be used for increasing the shear strength of existing members.

Member Strengthening Case Studies

Steel cover plates can be used in a variety of situations. They can be used to increase the section modulus of steel, reinforced concrete, and timber beams. Steel cover plates are also an effective method of strengthening compression members in trusses by providing additional cross-sectional area and by reducing the slenderness ratio of the member.

Mancarti (1982) reported on the use of steel cover plates to strengthen floor beams on the Pit River Bridge and Overhead in California. The truss structure required strengthening of various other components to accommodate increased dead load. Stringers in this bridge were strengthened by applying prestressing tendons near the top flange to reduce tensile stress in the negative moment region. This prestressing caused increased compressive stresses in the bottom flanges, which in turn required the addition of steel bars to the tops of the stringer bottom flange.

A report by Rodriguez et al. (1985) cited a number of cases of coverplating existing members of old railway trusses. These case studies included the inspection of 109 bridges and a determination of their safety. Some strengthening techniques included steel-coverplating beam members as well as truss members. Cover plates used to reinforce existing floor beams on a deficient thru truss were designed to carry all live-load bending moments. Deficient truss members were strengthened with box sections made up of welded plates. The box was placed around the existing member and connected to it by welding.

An unusually large number of masonry arch bridges in the United Kingdom have lead to the development of a technique of internal strengthening known as Archtec (Cole and Brookes 2001). This technique involves inserting and grouting in-place stainless steel reinforcing bars. The bars are grouted in a “sock” that ensures that the surrounding masonry is not displaced from the grouting pressure. Pull-out tests are typically performed to verify the in-place strength of the bars. Analytical studies and experience with more than 20 such rehabilitations have lead to the refinement of the construction procedures and confirmed the effectiveness of the procedure.

Post-Tensioning Various Bridge Components

Since the 19th century, timber structures have been strengthened by means of king post and queen post-tendon arrangements. These forms of strengthening by post-tensioning are still used today. Since the 1950s, post-tensioning has been applied as a strengthening method in many more configurations to almost all common bridge types.

Post-tensioning can be applied to an existing bridge to meet a variety of objectives. It can be used to relieve tension overstresses with respect to service load and fatigue-allowable stresses. These overstresses may be axial tension in truss members or tension associated with flexure, shear, or torsion in bridge stringers, beams, or girders.

Post-tensioning also can reduce or reverse undesirable displacements. These displacements may be local, as in the case of cracking, or global, as in the case of excessive bridge deflections. Although post-tensioning is generally not as effective with respect to ultimate strength as with respect to service-load-allowable stresses, it can be used to add ultimate strength to an existing bridge. Most often post-tensioning has been applied with the objective of controlling longitudinal tension stresses in bridge members under service-loading conditions.

The axial force, shear force, and bending moment effects of post-tensioning have enough versatility in application so as to meet a wide variety of strengthening requirements. This is most likely the only strengthening method that can actually reverse undesirable behavior in an existing bridge, rather than provide a simple patching effect. For both of these reasons, post-tensioning has become a commonly used repair and strengthening method.

Since the 1960s, external post-tensioning has been applied to reinforced concrete stringer and tee bridges. In the past 20 years, external post-tensioning has been added to a variety of prestressed, concrete-stringer, and box-beam bridges. Many West German prestressed concrete bridges have required strengthening by post-tensioning as a result of construction joint distress. Post-tensioning has even been applied to a reinforced concrete slab bridge by coring the full length of the span for placement of tendons ("Rehabilitation of Structure 41 . . ." 1983).

Lee (1952) reported on the use of the eccentric tendon for strengthening British cast iron and steel highway and railway bridges in the early 1950s. In Europe, a considerable number of bridges have been strengthened with this scheme. Linear post-tensioning on continuous spans has been used for deflection control or strengthening in Germany (Jungwirth and Kern 1980) and the United States (Mancarti 1984) since the late 1970s.

A king post system was used in Minnesota in 1975 to temporarily strengthen a steel-stringer bridge (Benthin 1975). It was possible to economically strengthen this bridge with scrap timber and cable for the last few years of its life before it was replaced.

Post-tensioning was first applied to steel trusses for purposes of strengthening in the early 1950s (Lee 1952), at about the same time that it was first applied to steel-stringer and steel-girder floor-beam bridges. Concentric tendons on individual members were first reported for the proposed strengthening of a cambered-truss bridge in Czechoslovakia in 1964 (Ferjencik and Tochacek 1975). For that bridge, it was proposed to strengthen the most highly stressed tension diagonals by post-tensioning. Lee (1952) described the use of a concentric tendon on a series of members for British railway bridges in the early 1950s, and there have been a considerable number of bridges strengthened with this scheme in Europe.

Most uses of post-tensioning for strengthening have been on the longitudinal members in bridges; however, post-tensioning has also been used for strengthening in the transverse direction. After the deterioration of the lateral load distribution characteristics of laminated timber decks was noted in Canada in the mid-1970s (Taylor and Walsh 1984), transverse post-tensioning was used to strengthen the bridge deck. A continuous steel channel waler on each edge of the deck distributes the post-tensioning forces from threadbar tendons above and below the deck, thereby preventing local overstress in the timber. A similar tendon arrangement was used in an Illinois bridge (Lamberson 1983) to tie together spreading, prestressed concrete box beams.

This overview of the uses of post-tensioning for bridge strengthening identifies the most important concepts used in the past and indicates the versatility of post-tensioning as a strengthening method.

When post-tensioning is used as a strengthening method, it increases the allowable stress range by the magnitude of the applied post-tensioning stress. If maximum advantage is taken of the increased allowable stress range, the factor of safety against ultimate load will be reduced. Therefore, the ultimate load capacity will not increase at the same rate as the allowable stress capacity. For short-term strengthening applications the reduced factor of safety should not be a limitation, especially in view of the recent trend toward smaller factors of safety in design standards. For long-term strengthening applications, however, the reduced factor of safety may be a limitation.

Post-tensioning does require relatively accurate fabrication and construction and relatively careful monitoring of forces locked into the tendons. Either too much or too little tendon force can cause overstress in the members of the bridge being strengthened.

A large percentage of the single-span composite steel-stringer bridges constructed in the United States between 1940 and 1960 has smaller exterior stringers. These stringers are significantly overstressed for today's legal loads. In some cases, the interior stringers are also overstressed to a lesser degree. Thus, post-tensioning is most likely only required for the exterior stringers; through lateral load distribution, a stress reduction is also obtained in the interior stringers.

By analyzing an under-capacity bridge, an engineer can determine the overstress in the interior and exterior stringers. This overstress is based on the procedure of isolating each bridge stringer from the total structure. The amount of post-tensioning required to reduce the stress in the stringers can then be determined if the amount of post-tensioning force remaining on the exterior stringers is known. Researchers at Iowa State University have developed a procedure for quantifying this through the use of force and moment fractions (Klaiber et al. 1983; Dunker et al. 1985a,b, 1986). This strengthening procedure has been used on several bridges in Iowa, Florida, and South Dakota. In all instances, the procedure was employed by local contractors without any significant difficulties (Beck et al. 1984; Klaiber et al. 1990a).

Similar to the single-span bridges, there are a large number of continuous-span composite steel-stringer bridges that also have excessive flexural stresses. Through laboratory tests at Iowa State University on a one-third scale, three-span continuous bridge it was determined that the desired stress reduction in most situations could be obtained by post-tensioning the positive moment regions of the various stringers (Dunker et al. 1987, 1990). In the cases in which there are excessive overstresses in the negative moment regions, it may be necessary to use superimposed trusses on the exterior stringers in addition to post-tensioning the positive moment regions. Similar to single-span bridges, force fractions and moment fractions are used in continuous-span bridges to determine the distribution of strengthening forces in a given bridge. As expected, the design procedure is considerably more involved for continuous-span bridges as transverse and longitudinal distribution of forces must be taken into consideration (Klaiber et al. 1990, 1993a,b; Planck et al. 1993; Wipf et al. 1995; El-Arabaty et al. 1996).

Miyamoto et al. (1998) described a technique for strengthening composite steel-stringer bridges using external prestressing. The application of these types of prestressing forces to composite steel girders has many of the same benefits of applying these forces to concrete structures. First, when the loadings are correctly applied, significant increases in moment capacity can be achieved. In addition, the elastic region of a given bridge system can be increased. Field testing verified that this is an effective technique for improving girder stress conditions.

Vernigora et al. (1969) reported that during an inspection of Bridge Number 3 over the Welland Canal in Ontario, Canada, the presence of diagonal shear tension cracks, spalling, and exposed reinforcing in the bridge beams was discovered. Four rehabilitation schemes were initially considered in an attempt to find the most economical solution. The schemes considered included decreasing span length by adding concrete "brackets," installing concrete knee frames to convert each simple span into three continuous spans, replacing the deck with precast/prestressed slab sections, and converting the existing simple spans into continuous spans by means of external post-tensioning. The last scheme was found to be the most cost-effective. By using the maximum practical eccentricity and greatest prestressing force there would be no tension at the critical section. The project was very successful, and the authors indicated that an added bonus of this type of strengthening was that all but one expansion joint was eliminated, thus reducing maintenance costs.

Developing Additional Bridge Continuity

Addition of Supplemental Supports Supplemental supports can be added to reduce span length and thereby reduce the maximum positive moment in a given bridge. By changing a single-span bridge to a continuous, multiple-span bridge, stresses in the bridge can be altered dramatically, thereby improving the bridge's maximum live-load capacity. Although this method may be quite expensive because of the cost of adding an additional pier(s), it may still be desirable in certain situations.

This method is applicable to most types of stringer bridges, such as steel, concrete, and timber, and has also been used on truss bridges (Sabnis 1983). Each of these types of bridges has distinct differences.

If a supplemental center support is added to the center of a 24.4-m (80-ft)-long steel-stringer bridge, which has been designed for HS 20-44 loading, the maximum positive live-load moment is reduced from 1580 kN·m (1,165 ft-kips) to 485 kN·m (360 ft-kips), a reduction of more than 69%. At the same time, however, a negative moment of 360 kN·m (265 ft-kips) is created, which must be taken into account. In situations where the added support cannot be placed at the center, reductions in positive moments are slightly less.

Depending on the type of bridge, there are various limitations in this method of strengthening. First, because of conditions directly below the existing bridge, there may not be a suitable location for the pier, as a result of, for example, the presence of a roadway or railroad tracks, poor soil conditions, the presence of a deep gorge, or stream velocity. This method is most cost-effective with medium- to long-span bridges and therefore may have limited application on low-volume roads.

The type of pier system employed greatly depends on the loading and also the soil conditions. A method employed by the Florida DOT (Roberts 1978) can be used to install the piles under the bridge with limited modification to the existing bridge. This method consists of cutting holes through the deck above the point of application of the piles. Next, piles are driven into position through the deck. The piles are then cut off so that a pier cap and rollers can be placed under the stringers.

Another major concern with this method is how to provide reinforcement in the deck when the region in the vicinity of the support becomes a negative moment region. If there is a noncomposite deck, the concrete deck does not carry any of the negative moment and therefore needs no alteration. For composite decks, the deck in the negative moment region should be removed and replaced with a properly reinforced deck.

Modification of Simple Spans In this method of strengthening, simply supported adjacent spans are connected together with a moment and shear-type connection. Once this connection is in place, the simple spans become one continuous span, which alters the stress distribution. The desired reduction in the positive moment, however, is accompanied by the development of a negative moment over the interior supports.

This method can be used primarily with steel and timber bridges. Although it could also be used on concrete-stringer bridges, the difficulties in the structural connecting of adjacent reinforced concrete beams make the method impractical. The stringer material and deck type dictate construction details. This method also reduces future maintenance requirements, because it eliminates a roadway joint and one set of bearings at each pier where continuity is provided (Berger 1978).

The main disadvantage of modifying simple spans is the negative moment developed over the piers. To provide continuity, one must design for and provide reinforcement for the new negative moments and shears, as well as the increased vertical reactions at the interior piers.

Recently, the Robert Moses Parkway Bridge in Buffalo, New York (Malik 1996), which originally consisted of 25 simply supported spans ranging in length from 19.2 m (63 ft) to 23.5 m (77 ft), was seismically retrofitted. Moment and shear splices were added to convert the bridge to continuous spans: 1 two-span element, 1 three-span element, and 5 four-span elements. This modification not only strengthened the bridge, but also provided redundancy and improved its earthquake resistance.

When providing continuity for shear and moment transfer in timber-stringers, steel plates can be placed on both sides and on the top and bottom of the connection and then secured in place with either bolts or lag screws. Additional strength can be obtained at the joint by injecting epoxy into the timber cracks as suggested by Avent et al. (1976).

Recent Strengthening Developments

Epoxy-Bonded Steel Plates Epoxy-bonded steel plates have been used to strengthen or repair buildings and bridges in many countries around the world including Australia, South Africa, Switzerland, the United Kingdom, and Japan. The principle of this strengthening technique is rather simple: an epoxy adhesive is used to bond steel plates to overstressed regions of reinforced concrete members.

Although this procedure has been used on dozens of bridges in other countries, as far as can be determined, it has not been used on any bridges in the United States, because of concerns with the method, such as plate corrosion, long-term durability of the bond connection, plate peeling, and difficulties in handling and installing heavy plates.

A summary of work around the world using epoxy-bonded steel plates for bridge strengthening is given by Eberline et al. (1989). The authors reported that a number of countries had used epoxy-bonded steel plates for the strengthening of concrete bridges. However, because little work of this kind has been undertaken in the United States, an overall synthesis of applications had not previously been completed. Information on the following topics, bonding procedures, impact of plate geometry, and effects of cyclic loading is included. In addition, numerous applications of this technique are presented, along with an extensive table summarizing where specific information can be found.

In recent years, the steel plates used in this strengthening procedure have been replaced with FRP sheets. The most interest has been in carbon-fiber-reinforced polymer (CFRP) strips.

CFRP Plate Strengthening CFRP strips have essentially replaced steel plates, because CFRP has none of the previously noted disadvantages of steel plates. Although CFRP strips are expensive, the procedure has many advantages, including

- Less weight,
- Strengthening can be added to the exact location where increased strength is required,
- Strengthening system requires minimal space,
- Material has high tensile strength,
- No corrosion problems,
- Easy to handle and install, and
- Excellent fatigue properties.

As research is still in progress in Europe, Japan, Canada, and the United States on this strengthening procedure, and because the application of CFRP strips varies from structure to structure, rather than providing details on this procedure, several examples of its application will be described in the following paragraphs.

The techniques of FRP plates are now established as a relatively simple rehabilitation and strengthening procedure that can significantly improve the shear and flexural performance of various types of structural elements. Bridge beams and slabs in particular have been strengthened using this technique. Swiss researchers are generally credited with doing the initial research on the use of FRP for strengthening (Meier and Kauer 1991). There are literally dozens of articles published on laboratory studies on the use of FRP for strengthening reinforced and prestressed concrete elements. Only a few of these will be presented in this document. The majority of the articles presented in this synthesis concern the field applications of FRP. One of the more comprehensive studies of an FRP strengthening system (essentially all aspects of materials, design, and analysis were covered) was undertaken in the United Kingdom (Hollaway and Leening 1999).

In 1994, legal truck loads in Japan were increased by 25% to 22.7 t (25 tons). However, after a review of several concrete slab bridges, it was determined that they were inadequate for this increased load level. Approximately 50 of these bridges were strengthened using CFRP sheets bonded to the tension face. The additional material not only reduced the stress in the reinforcing bars, it also reduced the deflections in the slabs because of the high modulus of elasticity of the CFRP sheets (Klaiber 1998).

Recently, a prestressed concrete beam in West Palm Beach, Florida, which had been damaged after being struck by an overheight vehicle, was repaired using CFRP. This repair was accomplished in 15 h over three consecutive nights with minimal disruption of traffic. The alternative to this repair technique would have been to replace the damaged prestressed concrete with a new prestressed concrete beam. This procedure would have taken about 1 month and would have required some road closures.

The Oberriet–Meiningen three-span continuous bridge over the Rhine River, connecting Switzerland and Austria, was completed in 1963. Because of increased traffic loading it was determined that the bridge needed strengthening. The strengthening was accomplished in 1996 by increasing the deck thickness 80 mm (3.1 in.) and by adding 160 CFRP strips 4 m (13.1 ft) long at 750 mm (29.5 in.) intervals to the underside of the deck. The combination of these two remedies increased the capacity of the bridge so that it is in full compliance with today's safety and load requirements.

Three severely deteriorated 70-year-old reinforced-concrete frame bridges near Dreselou, Germany, have recently been strengthened (increased flexure and shear capacity) using CFRP plates. Before strengthening, the bridges were restricted to 2-ton vehicles. With strengthening, 14.5-t (16-ton) vehicles are now permitted to use the bridges. Before implementing the CFRP strengthening procedure, laboratory tests were completed on this strengthening technique at the Technical University in Brauwschweigs, Germany.

The use of FRP deck panels as a means of increasing live-load capacity during the rehabilitation of an old thru truss bridge is discussed in Alampalli and Kunin (2001). New York State is currently exploring innovative solutions to extend the service life of existing structures. Many of the bridges are considered deficient because of poor deck conditions or weight restrictions. One of the bridges retrofitted with a lighter deck system is a simply supported Warren steel truss, 42.7 m (140 ft) long, 7.3 m (25 ft) wide curb-to-curb, and skewed 27 degrees. The deck system is a cellular core product. The existing deck and asphalt overlays weighed a combined 830 kg/m^2 (170 psf), whereas the FRP retrofit deck weighed only 156 kg/m^2 (32 psf). This light deck, in conjunction with minor retrofit to the steel superstructure, was sufficient to remove the load restrictions and extend the service life of the bridge.

Because this was the first FRP deck used on a state highway in the United States, conservative design assumptions were used and a field testing program was implemented to verify performance of the completed structure. The field test objectives were to determine if composite action occurred between the deck and floor beams, determine the effectiveness of the joints between panel segments, verify the deck load rating, and acquire strain data for calibration of a finite-element model. Test results indicated no composite action between the deck and floor beams. Additionally, the test results indicated incomplete load transfer between adjacent panels along the epoxied longitudinal joint.

This study of redecking an aging truss bridge with FRP deck panels indicated that the deck was effective at allowing a previously load-restricted bridge to remain in service without weight restrictions. The deck was installed in 1 month, reduced the bridge dead load by 240 400 kg (265 tons), and cost $800,000, as compared with $2.2 million estimated for a replacement structure.

Work completed at the Georgia Institute of Technology by Zureick (1999) determined that FRP materials can make bridges 30% to 40% stronger than the original design. Ongoing work includes exposing FRP components to extreme environmental conditions. Results from these studies will be used to develop predictive models for FRP life spans. Zureick is also aiming to develop national guidelines for the use of FRP materials in repair projects.

Halstead et al. (1999) described a unique project in which six FRP manufacturers participated in a demonstration project aimed at determining whether the application of FRP wraps provides an efficient, cost-effective solution for the short-term rehabilitation of bridges. The test site, a series of deteriorated columns in Owego, New York, was evaluated for four options of repairing the damaged columns. The four options, column replacement, concrete repair, steel jacketing and wrapping with FRPs, were evaluated for their cost-effectiveness. FRP was found to be the most economical for the short duration the repair was needed to remain in service.

Based on numerous field projects, Shahawy et al. (2001) presented a series of guidelines that an engineer can follow when recommending construction of FRP-based projects. These recommendations, which are based on 10 years of field applications, give information on the selection of FRP components from both environmental and economic viewpoints. In addition, they cite the general factors that must be considered during general preparations (e.g., ambient temperature, condensation, surface defects and corners, primer and resin, handling of FRP sheets, and section preparation). They further explain the general procedures required to install and inspect these materials.

In a field test to determine the effectiveness of externally bonded FRP plates on a reinforced concrete bridge, Stallings et al. (2000) found that the retrofit was a simple and straightforward process that reduced reinforcing steel stresses from

4% to 12% and girder deflections from 2% to 12%. Using classical cracked-section moment of inertia calculations, the moment of inertia was determined to increase by only 5%. Therefore, it was concluded that more advanced procedures are needed to accurately determine the benefit of FRP plates.

Triantafillou and Antonopoulos (2000) have presented a simple design model for determining the contribution of FRP to the shear capacity of strengthened reinforced concrete elements. The proposed model predicts the FRP contribution in an analogy to conventional shear reinforcement. It was shown that this proposed model gives better agreement with most available test results than previously proposed models.

The use of an FRP composite deck on existing precast concrete beams took place on Five Mile Road in Hamilton County, Ohio (2001). This project was unique in that a method of attaching the FRP deck panels to the existing concrete beams was developed. The concrete beams also had to have a thicker top flange added to increase their stiffness because the FRP deck did not contribute to the structural rigidity the way concrete decks do.

Hassan and Rizkalla (2002) investigated the effectiveness of five different FRP systems in strengthening half-scale models of prestressed concrete bridge slabs. Systems investigated were

- Two types of CFRP bars installed and bonded in shallow “near surface” grooves,
- Externally mounted CFRP strips,
- “Near surface” mounted CFRP strips, and
- Externally bonded CFRP sheets.

Based on their experimental investigation, the following conclusions were made:

- Externally bonded CFRP sheets are the most efficient technique in terms of increased strength and lower construction costs.
- Use of near surface mounted CFRP reinforcement (installed in small grooves immediately below the existing surface) is feasible for strengthening or repairing prestressed girders or slabs.
- Stiffness and strength of concrete slabs strengthened with CFRP materials were substantially increased.
- Magnitude of strength increase was influenced by the type and configuration of the CFRP materials.
- Strengthening using externally bonded CFRP strips provided the least increase in strength (11%) as a result of the peeling of the strips from the concrete.

Currently, the authors are working on design guidelines for determining the developmental length needed for the various proposed FRP strengthening techniques.

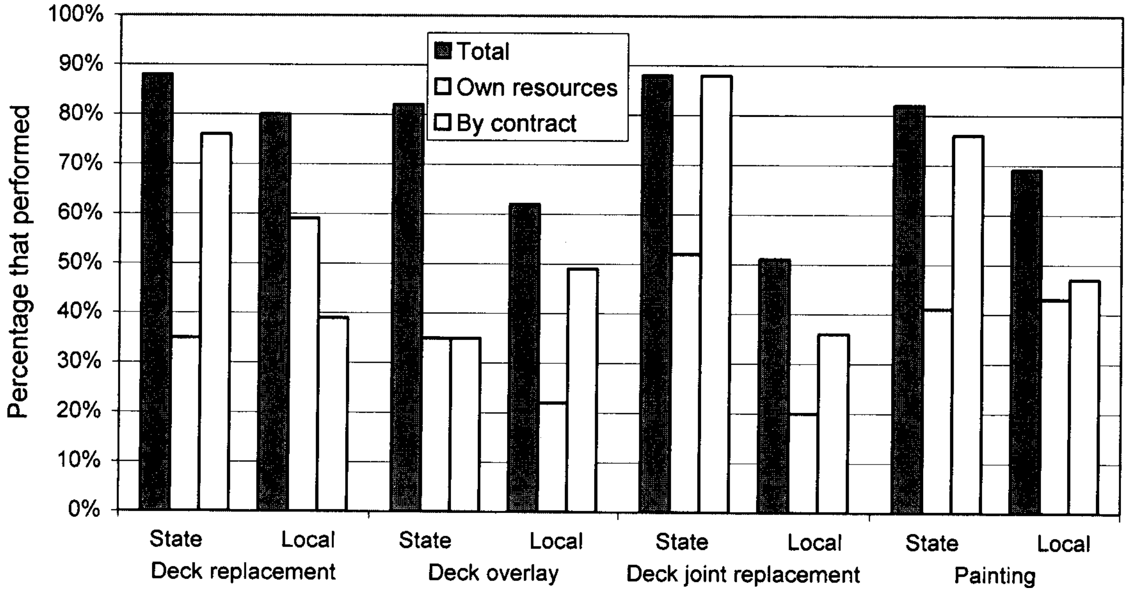
Through laboratory tests, Miller et al. (2001a) determined the effectiveness of bonding CFRP plates to the tension flanges of steel bridge girders to increase their stiffness and strength. The durability of the bonded CFRP plates to various environmental conditions and fatigue was also determined. Increases in stiffness ranging from 10% to 37% were achieved in the laboratory. As a result of the successful laboratory study, one of the steel beams of the I-95 bridge over Christiana Creek outside of Newark, Delaware, was strengthened with CFRP plates. To determine the effectiveness of the added CFRP plates, diagnostic load tests were performed before and after their installation. Based on test results, the retrofit produced an 11.6% increase in the global flexural stiffness. Test results to date indicate that the procedure is very promising.

Hag-Elsafi et al. (2001) of the New York State DOT reported on the use of FRP laminates to contain freeze–thaw cracking and to improve the flexural and shear strength of a reinforced concrete T-beam bridge built in 1932. Load tests were conducted before and after the laminates were installed to evaluate the effectiveness of the strengthening system. Based on the load tests, it was determined that when the bridge was subjected to service loads, the strengthening system slightly reduced the stresses in the longitudinal reinforcement and moderately improved transverse live-load distribution. In this project, the FRP strengthening was found to be cost-effective ($300,000 for the rehabilitation vs. $1.2 million for a replacement structure), with essentially no interruption of traffic.

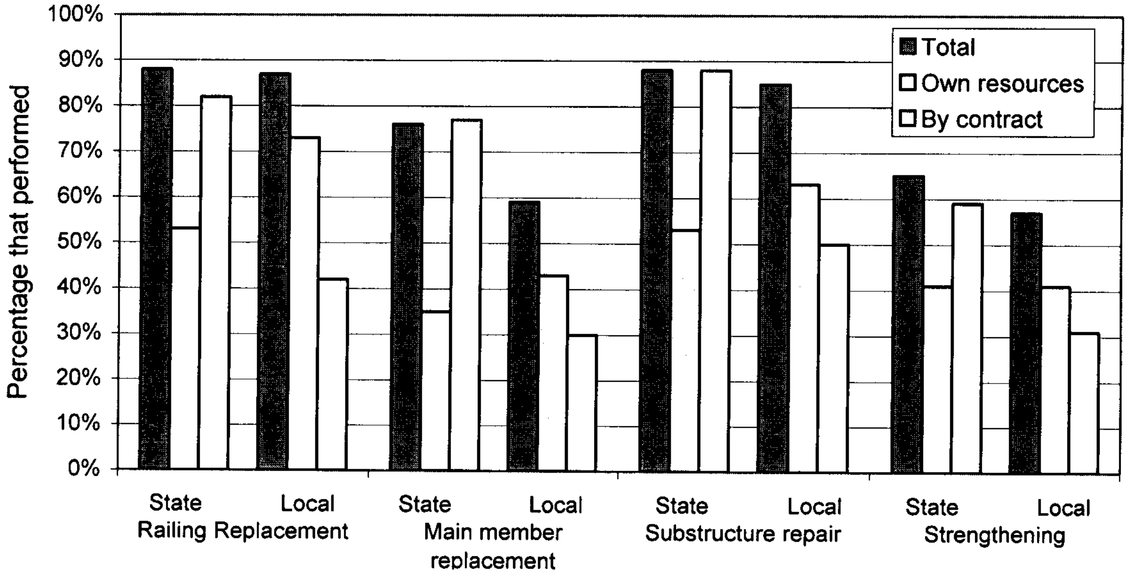
Two different documents are currently being prepared to assist engineers in the use of FRP in the repairing of reinforced concrete structures. ACI (American Concrete Institute) Committee 440—Fiber-Reinforced Polymer Reinforcement—has prepared guidelines for the use of FRP in the strengthening of concrete structures (*Guide for Design . . .* 2003). These guidelines are currently out for review. Mirmiran et al. (2004) has published the final report for NCHRP Project 10-59, research done to develop recommended construction specifications and a construction process control manual for bonded FRP report and retrofit of concrete structures (*NCHRP Report 514*: *Bonded Repair and Retrofit of Concrete Structures Using FRP Composites*: *Recommended Construction Specifications and Process Control Manual*).

Bridge Owners Survey Results: Rehabilitation and Strengthening Work Performed

The agencies surveyed indicated the types of rehabilitation and strengthening work they have performed and whether they used their own resources or contracted for the work. A summary of the responses is shown in Figure 10. The plots are shown for various types of rehabilitation and strengthening work performed and are summarized for state and



a) Group I



b) Group II

FIGURE 10 Types of rehabilitation/strengthening experience by state and local agencies.

local respondents. Each of the state and local responses are presented three ways: (1) the total percentage of respondents who have done the work, (2) the percentage of those respondents who have used their own resources for the work, and (3) the percentage of those respondents who have used contract forces for the work. Note that the responses related to the use of in-house resources and the use of contract resources are independent; therefore, the percent total is not additive for items 2 and 3. In other words, all of the responses represent only those who have used the various means to accomplish the work.

Most states performed a high percentage of rehabilitation and strengthening on all of the bridge components shown, indicating that main member replacement and strengthening are at the lower end of their efforts. Most of the work is performed by contract forces, except for deck overlays where an equal percentage of work is undertaken by both in-house and contract forces. As can be seen in Figure 10b, of those responding, both state and local agencies have completed large numbers of strengthened projects.

The responses to the same questions from the local agencies were similar to those from the state in terms of the total percent of effort in rehabilitation of the various bridge components. One exception was that local agencies performed significantly less work related to deck overlays, deck joint replacements, and main member replacement than did the state agencies. The local agencies also tended to use more of their own resources than the states. In particular, the local agencies relied more on their own resources than on contract resources for deck replacement, railing replacement, main member replacement, substructure replacement, and strengthening.

CHAPTER FOUR

BRIDGE REPLACEMENT ALTERNATIVES

This chapter explores the various aspects of off-system bridge replacements. Included in the discussion are the design rules as they apply to the geometric and structural design of the bridges; experiences and opinions of bridge owners regarding decisions made in the bridge replacement process; an extensive discussion of literature relevant to off-system bridge replacements; a discussion related to innovative concepts for bridge replacements; and finally a section on the use of software, standard plans, and design aids to expedite the design and construction of off-system bridges.

PREVIOUS WORK: A LITERATURE REVIEW

Previous work on the determination of economical solutions to the off-system and low-volume road bridge problem has been conducted. Several of these references are discussed in the context of general information, and specific solutions are presented later in this chapter along with results of the project survey.

NCHRP Reports 222 and *243* (University of Virginia 1980, 1981) are companion reports that specifically addressed the problems of bridge rehabilitation and replacement on low-volume roads. Both of these reports were products of NHCRP Project 12-20, Bridges on Secondary Highways and Local Roads—Rehabilitation and Replacement. The focus of the project was to identify common local road bridge deficiencies, evaluate feasible corrective procedures, evaluate economical bridge replacement systems, and develop decision trees to assist local agency engineers in making repair or replacement decisions. Only the findings and recommendations relevant to bridge replacement are discussed in this chapter.

In *NCHRP Report 222*, the significant focus is on repair and bridge replacement, with the primary emphasis on bridge superstructures. The first step in the bridge selection process is determining the “most appropriate” alternative for the specific project objectives. The objectives identified as worthy of consideration for all bridges are required structural capacity, traffic volume, anticipated future use, labor requirements for construction, and cost. Additional factors can include familiarity with the bridge type considered, available contractors, budget, material availability, and environmental priorities; some of the factors that might be considered in the development of work priorities on a system of bridges and in the selection of the appropriate type of replacements.

In the specific chapter concerning bridge replacement systems, *NCHRP Report 222* discussed a series of options including concrete, steel, and timber bridge superstructure replacement systems, as well as some miscellaneous forms of construction such as bridge substructures, deck forming, bridge railings, and buried pipes and conduits. A total of 27 bridge replacement systems are identified, each one being briefly discussed and cross referenced to another source of greater detailed information.

In general, the *NCHRP Report 222* bridge replacement options are fairly standard forms of construction, as one might expect from a report reviewing low-volume road bridge replacements. The concrete bridge options include precast slabs and box beams, as well as prestressed products such as double-tee, channel beam, multi-stem beam, single tee, bulb tee, and I-girders. All of these systems have their requisite pluses and minuses, many of which are identified in the NCHRP report. For steel bridges, some of the options presented are no longer likely to represent cost-effective choices because of their complicated fabrication. Some of the options shown, including steel decking with asphalt paving on top of multiple stringers, timber decks of several forms over steel beams, steel grid decks, and several types of precast concrete decking, in addition to conventional CIP concrete, are appropriate off-system bridge replacements. The timber bridge options include glue-laminated timber I-beam construction, nail-laminated timber slab bridges with a wearing surface, solid sawn-timber bridges with decking, and a form of construction that in many ways resembles building framing that uses plywood decking on top of timber planks, which then rest on the main stringers.

The follow-up to *NCHRP Report 222* was *NCHRP Report 243*, which essentially focused on an expansion of repair techniques and presented only a few minor additions to the list of replacement systems identified in the earlier report.

Wipf et al. (1994) presented research results concerning the evaluation of suitable options for county bridge replacements and also developed new bridge concepts based on the desired characteristics of county bridge replacements. The study endeavored to determine the reasons for bridge replacement, bridge replacement types and costs, participation of local forces in design and construction, expected life, foundation types, and degree of satisfaction of county bridge owners with various bridge types.

Following this information gathering process, several new bridge types were developed that met the objectives of county engineers. Additionally, standard solutions already in use were presented along with a brief discussion of the design and construction characteristics of each type.

Based on the project survey of county engineers in Iowa and surrounding Midwestern states, conducted by Wipf et al., the most common reasons for bridge replacement were insufficient load capacity, excessive deterioration, and inadequate roadway width. More than three-quarters of the respondents indicated insufficient capacity was the primary reason for replacement.

The most common replacement option for inadequate bridges noted by the survey respondents was a continuous concrete slab bridge, with 36% of deficient bridges being replaced with this kind of construction. Second, with a use rate of 31%, were prestressed beam bridges. Concrete culverts were third, being cited as the replacement option 17% of the time. Other types of replacement options such as timber, reinforced concrete, corrugated metal pipe (CMP), and low-water stream crossing completed the balance of choices. Costs for these various bridge replacement options were also compiled. Using cost data from the early to mid-1990s, prestressed girder construction was found to be the most expensive bridge type, with unit costs for the entire bridge averaging approximately $\$624/\mathrm{m}^2$ ($\$58/\mathrm{ft}^2$). The next most expensive type was a concrete slab at a cost of $\$540/\mathrm{m}^2$ ($\$50/\mathrm{ft}^2$). The remaining options, in descending cost order, were precast reinforced concrete bridges, steel-stringer bridges, and timber-stringer bridges. The costs and relative costs were believed to be accurate, because they all reflected construction costs for short span bridges.

Concerning the ability of local counties to construct the various bridge types, only the two most common bridge types were examined. The sample sizes for steel stringers, reinforced concrete girders, and timber bridges were not large enough to draw meaningful conclusions. Only 12% of reinforced concrete slabs and 14% of prestressed beam bridges were constructed by county employees; the primary reasons being inadequate supplies of heavy equipment and/or requirements for extensive formwork. Counties were queried as to their capabilities to construct bridges as it related to available equipment. With in-house equipment, the typical bridge that could be constructed would be in the 12 m (40 ft) range and would be founded on timber piles. With rented equipment, both the bridge size and pile size could be increased, as well as the type of pile.

Foundation types were also explored, and it was determined that the two most common foundation types were steel H-piles and timber piles. Steel piles were only used on contractor-constructed bridges, whereas timber piles were used on both contractor- and county-built bridges. Spread footings and concrete piles are used sparingly and neither has been constructed with county forces.

GangaRao and Hegarty (1987) presented a series of recommendations for design and construction of low-volume road bridges. The premise of their work was that the existing AASHTO *Standard Specifications* did not reflect the uniquely different requirements for the design of low-volume road bridges.

GangaRao and Hegarty explored four critical decision points that affected the total cost and anticipated value of low-volume bridges: design specifications, number of components, materials, and safety features.

The authors noted that the AASHTO *Standard Specifications* were too conservative with respect to the design of low-volume road bridges, specifically the provisions related to fatigue, impact, lane load, and deflection criteria of existing codes.

For fatigue they recommend the use of the lowest number of fatigue cycles or neglecting fatigue entirely. They justified this by considering the low traffic volumes and the infrequent cycles of heavy vehicles. They also discussed the impact factor and recommended that it be taken as a constant 30%. This is the high end of the impact factors specified in the *Standard Specifications* and slightly less than that used in the load and restriction factor design (LRFD) *Specifications*, 33%. The relevance of the AASHTO *Standard Specifications* lane load was discussed. Because this loading was intended to represent a string of vehicles, that is, a truck train, it was suggested that it could be neglected for the design of low-volume road bridges. This is not necessarily a substantive change in design for most low-volume road bridges because the lane load provisions do not control flexural or shear design of simple span bridges of usual low-volume road span lengths. Finally, a relaxation of the live-load deflection requirements was proposed to a level consistent with that used in building design, L/360. This is based on the infrequent use of a given bridge by more than one vehicle at a time.

Concerning bridge geometric standards, GangaRao and Hegarty advocated consideration of the design of one-lane bridges with roadway widths of 3.6 to 4.6 m (12 to 15 ft), with the caveat that for bridges with significant agricultural or commercial use, high speeds or poor alignments, or in the vicinity of future development, considerations should be given to the construction of wider bridges. They also discussed the possibility of constructing one-lane bridges on two-lane roads, although this is strongly discouraged by most other sources. The justification for a narrower bridge was economic and was based on the anticipated savings in bridge materials.

The selection of proper structure types for low-volume road bridges was approached from the perspective of economics and durable choices for bridge decks, superstructures, and substructures.

For bridge decks, the most appropriate deck type will be one that is easily obtained from local sources, is familiar to construction and maintenance crews, and is economically attractive. Regional factors are involved and therefore the appropriate deck type is not a single choice. The several deck types that are considered viable, in addition to CIP concrete, include precast and prestressed deck panels, open steel grid decks, and glulam deck panels. Concrete-filled steel grid decks were discounted by GangaRao and Hegarty, although there is evidence to suggest that they too are viable choices.

Concerning bridge superstructures, the bridge types discounted included exotic forms such as cable-supported structures and also built-up steel sections (plate girders) and truss bridges. The authors also discounted precast reinforced concrete members because of their short span length limitation and structural inefficiency as compared with prestressed members in similar span ranges. This synthesis reaches other conclusions relative to both the truss and precast reinforced concrete bridges. The availability of prefabricated truss bridges composed with weather-resistant construction (galvanized or self-weathering steel) are economic choices in some locations, again given the proximity to the fabricator. Also, although admittedly inefficient as compared with prestressed bridges, the ability to locally fabricate precast reinforced concrete members using local forces, sometimes very close to the eventual bridge, is an advantage that is not outweighed by arguments of structural efficiency. GangaRao and Hegarty do advocate the use of prestressed beams, as previously mentioned, as well as glulam stringers and rolled shape steel sections. Various combinations of these beam types and aforementioned deck systems are appropriate depending on the required span length and the availability of the various materials.

For bridge abutments, a comparison between stub and full-height vertical abutments was made. It was concluded that unless an entire span could be eliminated through the use of the full-height abutment, the economics are usually in favor of the stub configuration. Also, deep foundations are not advocated for low-volume construction as the cost of pilings could be offset by larger spread footings. (Caution should be exercised however when scour is a consideration.) Integral abutments on piles and jointless stub abutments are only briefly mentioned but may be the most economical choice from both a first cost and total ownership cost perspective.

DESIGN RULES FOR OFF-SYSTEM BRIDGES

The design policies for off-system bridges are discussed in this section. The information presented is a combination of regulatory information relative to minimum design standards and responses from surveyed agencies describing their actual design practices.

With the exception of bridges on the NHS, bridges specifically not addressed in this study, there is no federal mandate regarding minimum design standards. In Title 23 USC 109, "Standards," the regulations regarding design standards are established. Specifically, 23 USC 109(o) "Compliance with State Laws for Non-NHS Projects" states the following:

> Projects (other than highway projects on the National Highway System) shall be designed, constructed, operated, and maintained in accordance with *State laws* (emphasis added), regulations, directives, safety standards, design standards, and construction standards.

The requirements of 23 USC 109(o) are similar to those stated in 23 CFR 625—*Design Standards for Highways* (1999). Specifically, 23 CFR 625.2(b) concerns design criteria for 3R projects. It states that

> . . . [projects] shall be constructed in accordance with standards which preserve and extend the service life of highways and enhance highway safety. [Work] includes placement of additional surface material and/or other work necessary to return an existing roadway, including shoulders, bridges, the roadside, and appurtenances to a condition of structural or functional adequacy.

FHWA Federal Aid Policy Guide NS 23 CFR 625, Non-Regulatory Supplement indicates that for non-NHS projects "the states are strongly encouraged to consider and apply these provisions [23 USC 109(o)] in developing and applying their non-NHS standards." The implication of this statement is clear, even though the federal regulations are not applicable to non-NHS projects; the FHWA considers the NHS level standards as reasonable standards for non-NHS projects as well. The FHWA guide further indicates, although this again is for NHS-level structures, the following desirable objectives for new, reconstructed, or rehabilitated bridges:

- Bridge widths—The geometric standards referenced are those mandated by 23 CFR 625, specifically the AASHTO *Green Book*. Flexibility is provided for bridge width for 3R projects.
- Treatment of existing bridge on 3R projects—Each bridge should be assessed for structural and functional adequacy considering minimum bridge widths for retention of the existing structure and the suitability of the existing rail system. Upgrading of obsolete railings is strongly encouraged. Rehabilitated bridges should be designed to a minimum of M 13.5 (H 15)

> and have a minimum service life of 15 years. Bridge replacements should be in accordance with the latest AASHTO standards.

Again, although not strictly applicable to non-NHS structures, these recommended practices represent a framework of reasonable design objectives and standards that can be modified on a case-by-case basis.

In survey question DCF-1 agencies were asked to comment on the need to develop revised design guidelines for low-volume road bridges. Several of the responses focused directly on the issue of design loading. Some of the suggestions and requests submitted included the need for more appropriate low-volume road bridge railings consistent with the design speeds and vehicle types found on such roads. Suggestions were also made that bridges built for wide vehicles that use the bridges infrequently need not be designed based on their width for multiple lanes of live load. Several responses were in favor of keeping the minimum AASHTO loadings currently in use.

One of the issues explored in this project through the survey was the area of concern for liability, when other than the most current design criteria are used for new projects (or presumably allowed to be maintained during a 3R project). Survey question DCF–3 queried owners as to whether the reason for not using other than current design criteria was because of liability concerns. Of the responses, 44% of the state and 66% of the local agencies indicated concern for liability when published design standards were not used.

There seems to be general concern over the legal exposure of not using current design rules but an equal admission that little can be done to solve all problems at once given the pervasive nature of inadequate structures and roadway geometries. One comment indicated that in some cases bridges that should be rehabilitated have not been, because rehabilitation requires an upgrade of the structure to modern design standards, the cost of which is prohibitive. Fewer improvements are made because of this stipulation, which is certainly not the desired result. Other owners indicated that they knowingly spend much more money on bridge replacements than they believe is warranted as a safeguard against possible liability. There is no indication that state or local agencies believe in the construction of substandard structures, but the implication is that a modified design standard for off-system or low-volume bridges may be appropriate.

Geometric Design Rules

Geometric design rules and guidance from several sources are discussed here. These include the traditional AASHTO *Green Book* and other sources.

AASHTO Guidance

Although not a bridge design manual, the AASHTO *Green Book* discusses minimum roadway widths at bridges, as well as the recommended minimum structural capacities for new bridges and existing bridges to remain in service. The recommendations are explicitly restricted to bridges of less than 30 m (100 ft) in total length. The recommendations are presented in the context of the roadway classification, specifically local roads and streets, collector roads and streets, rural and urban arterials, and lastly freeways. Because the focus of this project is off-system bridges, the freeway/Interstate level structure criteria will not be discussed. It should be noted that AASHTO also recently published geometric design guidelines for low-volume roads with average daily traffic (ADT) of less than 400 vehicle per day (vpd). The guide was not available at the time this synthesis was prepared.

The *Green Book* establishes two-level criteria for bridge geometrics and minimum acceptable capacities, one level for new or reconstructed bridges, the other for bridges to remain in place. For new structures, the minimum recommended design loading for all classes of bridges is MS 18 (HS 20). For bridges to remain in place, with the exception for very low volumes (0–50 vpd) on local roads, the minimum recommended capacity for bridges to remain in place is MS 13.5 (H 15). When a road is to be reconstructed and the existing bridge is consistent with the proposed alignment and profile, the bridge may remain in place when its structural capacity meets the tolerable criteria, an example of which is presented in Table 3 for local rural roads. Similar tables exist for other functional classifications such as collector and arterial roads.

Some of the factors to consider when deciding whether to retain an existing bridge include the remaining life, cost of replacement, consideration as to whether the highway improvements will promote design speeds inconsistent with bridge safety features, accident history, and the aesthetic and historical significance of the bridge. Although no specific recommendations are given with respect to roadway width and minimum design loading, for structures in excess of 30 m (100 ft), additional criteria that may be relevant in the decision-making process including pedestrian volume, snow storage, design speed, crash history, and other features unique to the site.

FHWA Guidance

The FHWA has published a guide, *Flexibility in Highway Design* (1997), to both protect the scenic, historic, and other environmental features of existing highways or along proposed routes and promote safety and levels of service required of a modern transportation facility that address the

TABLE 3
RECOMMENDED MINIMUM GEOMETRIC AND STRUCTURAL CAPACITIES FOR LOCAL RURAL ROADS
(*A Policy of Geometric Design of Highways and Streets* 2001)

Criteria	Design Volume (vpd)	Minimum Clear Roadway Width of Bridge	Design Loading
New or reconstructed bridges	<400	Traveled way + 0.6 m (2 ft) each side	MS 18 (HS 20)
	400–2,000	Traveled way + 1.0 m (3 ft) each side	MS 18 (HS 20)
	≥2,000	Approach roadway width	MS 18 (HS 20)
Bridges to remain in place	0–50	6.0 m (20 ft)	M 9 (H 10)
	50–250	6.0 m (20 ft)	M 13.5 (H 15)
	250–1,500	6.6 m (22 ft)	M 13.5 (H 15)
	1,500–2,000	7.2 m (24 ft)	M 13.5 (H 15)
	≥2,000	8.4 m (28 ft)	M 13.5 (H 15)

choices engineers can make to achieve the various objectives. Essentially a guidebook tied to the AASHTO *Green Book*, but illustrating the flexibility of applying the criteria instead of strict rigid interpretation, the FHWA publication provides a valuable commentary and has various case studies of successful projects that have integrated the various environmental and safety aspects of transportation engineering. Much of the flexibility in highway and bridge design available to local road designers stems from the legislative provisions of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) legislation as well as the NHS Designation Act of 1995. Specifically, states may develop criteria they deem appropriate for projects not on the NHS system. Although the flexibility to develop standards apart from those recommended by the *Green Book* is present, many states have adopted design criteria for non-NHS structures that are similar to those used on the NHS system.

The FHWA guide briefly addresses the issue of tort liability. Published standards are typically used in tort cases as a basis for educating the public as to reasonable standards of care to be exercised in highway design. This does not imply that strict adherence to published standards is an absolution of liability nor does it imply that deviation from the standards constitutes liability. Defense of deviation from the standards is most effective when it centers on the inapplicability of the standards for a sound reason; economic hardship is not a persuasive argument.

Sample of State Policies

State interpretations of New York and Pennsylvania of the flexibility provided for non-NHS bridges are compared here. Both are eastern states with large metropolitan areas, large bridge populations, extensive road networks, and significant lane mileage and bridge counts in largely rural areas. Both states have significant off-system road and bridge problems and are given the same flexibility to develop local road system design guidelines. Copies of the local road design guidelines were obtained for both states.

The New York State guidelines (*Highway Design Manual* . . . 1999) are specifically restricted to the geometric design of locally owned low-volume highways with ADT of less than 400 vpd and may be used on all such projects regardless of funding source. The NYSDOT manual classifies low-volume roads in a number of different categories including Low Volume Collector, Residential Access, Farm Access, Resource/Industrial Access, Agricultural Land Access, and Recreational Land Access. Depending on these classifications, the types of vehicles using the road, and ADT, an Operational Type is assigned ranging from a Type A–C facility. Type A roads are two-lane, two-way facilities with the highest design speeds and provisions for opposing vehicles to pass at safe operating speeds. Type B roads are two-lane, two-way roads with speeds and operational characteristics appropriate for local streets. Finally, the Type C roads are single-lane, one-way or two-way roads with local road design speeds.

For approach roadway and minimum bridge widths, the NYSDOT manual recommends traveled way widths of from 3.0 m (10 ft) for Type C roads to 6.0 m (20 ft) for Type A roads. Lane, shoulder, and clear zone widths are also specified for each road type as is the recommended paving material, either asphalt concrete or aggregate surfacing. It is recommended that in the case of anticipated farm vehicle use a minimum bridge width of 6.0 m (20 ft) be used.

The Pennsylvania DOT policy was also examined (PennDOT 2000). The PennDOT procedure does not subdivide low-volume roads into various types as did the NYSDOT manual, rather all bridges with less than 400 vpd are treated the same, with distinctions made for urban or rural situations. For replacement bridges, similar to the criteria described previously for the state of New York, the minimum roadway width for collector and local roads is specified to be 7.2 m (24 ft), whereas the NYSDOT maximum width is 6.0 m (20 ft). The minimum required structural capacity is a PennDOT modified version of the AASHTO LRFD loading, designated PHL-93.

Comparison of these two states with very similar needs and existing conditions shows the great latitude these states have exercised in developing local road design standards. This synthesis does not endorse either approach, but it appears reasonable that some latitude in selecting bridge widths and design loading for low-volume rural or urban bridges should be provided.

Agency Survey Responses

Agencies were queried to provide insights into their geometric design policies. The AASHTO *Green Book* is followed by 56% of state and 70% of county respondents. Comments received concerning geometric design policy included a statement from West Virginia that their local road design policy allows for bridge geometrics that are automatically functionally obsolete. Responses from Maryland, Illinois, and New York indicated the use of design policies specifically developed for local roads and low-volume bridges. Only 47% of state and 9% of local agency responses indicated that published policies were in use.

Structural Design Criteria for New Bridges

Structural design criteria are discussed here with respect to the design for vehicular vertical loads as well as for the structural design of bridge railings. One of the concerns expressed in the development of this project was related to the level of design loads used in the design of off-system bridges. The current design policies commonly in use are presented in the following sections.

Design for Vehicular Loads

At present there are two primary design specifications for bridge structures, the AASHTO *Standard Specifications for Highway Bridges*, 16th edition (1996), and the LRFD *Bridge Design Specifications*, 2nd edition (1998). The *Standard Specifications* have been in continuous use for 70 years and have the traditional allowable stress and load factor design approaches for highway bridges. The *Standard Specifications* remain the predominant bridge design specification in use today. In 1994, AASHTO introduced a new specification, the LRFD *Specifications*, intended to replace the *Standard Specifications*. This new specification was based on probability theory when possible and calibrated to successful past practices to ensure a more uniform level of safety among structures of various materials, span ranges, bridge widths, etc. The new specifications resulted however in significant changes in loading, load distribution, load combinations and, in some cases, design methods from those found in the *Standard Specifications*. At this time the LRFD *Specifications* are not universally adopted by the states, with various levels of adoption from full use to no use at all.

Regarding the actual design loads used by the various specifications, the *Standard Specifications* uses either the common “M/H” or “MS/HS” classes of loading. The M/H series loads prescribed by AASHTO are M 13.5 (H 15) and M 18 (H 20), the number representing the gross vehicle weight in metric tons (t). For the MS/HS classes, the number represents the weight of the tractor portion of the semitrailer combination. The AASHTO prescribed loads are MS 13.5 (HS 15) and MS 18 (HS 20). In recognition of heavier truck loads as routine vehicles and as special permit vehicles, a number of states and presumably some local agencies have increased the AASHTO loading class. The most common modified design load is an MS 22.5 (HS 25) vehicle, which is a 25% increase in loads over that prescribed by AASHTO.

Along with the introduction of the LRFD *Specifications* came a new set of live loads. The notional loading, known as HL93, is a hybrid of the *Standard Specifications* live loads as it simultaneously involves a combination of truck and lane loads. Instead of the live loads being an either/or choice of truck or lane loads, they are now combined together in a single live-load model whose effects are significantly greater than the older MS 18 (HS 20) loadings, but not much different than MS 22.5 (HS 25) when considering the additional LRFD changes in load factors, load combinations, impact, and load distribution to the individual girders.

It was of interest to determine the current structural design policies of the agencies surveyed. Approximately one-third of state and one-fifth of local agency respondents indicated that structural design criteria other than the AASHTO *Standard Specifications* were used. Although agencies were not specifically asked what alternate design standard is used, it can be assumed that owing to the slow implementation of the LRFD *Specifications* at even the state level, currently used design standards for local bridges would be some variant of the AASHTO *Standard Specifications*. When specifically asked if the agency had published exception criteria, 29% of state and 6% of local agencies responded affirmatively.

Railing Design Loads

The design of railings has also evolved with changes in specifications. Properly designed railings must prevent the vehicle making contact with the railing from leaving the bridge and, as importantly, from being redirected back into the roadway or into oncoming traffic. The railings must be designed for both structural and functional requirements.

Although static force design procedures have been used in railing design for years, that is, the AASHTO *Standard Specifications* 45 kN (10 kip) criteria, modern design procedures use dynamic crash tests as more appropriate measures of railing performance.

In 1981, NCHRP published *NCHRP Report 230: Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances,* which outlined the crash test requirements for roadside hardware. At that time, *NCHRP Report 230* procedures did not mandate the use of crash testing in the design of roadside hardware. Following crash test failures of some systems designed in accordance with static design procedures, the FHWA began in 1986 to require that all bridge railings used on federal-aid projects meet crash test criteria and be tested accordingly. A tentative list of 22 crash-tested bridge railings was released with the 1986 memorandum.

In 1989, AASHTO published the first national design specification for bridge railings based on crash tests. The *Guide Specifications for Bridge Railings* (*Guide Spec*) prescribed a series of performance levels (PL) for bridge railings ranging from the PL-1 to PL-3, with PL-1 being the least demanding criteria and PL-3 the most demanding. Subsequent to the *Guide Spec* publication, NCHRP published *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features,* which prescribed six test levels (TL) from TL-1 to TL-6, with TL-1 being the least restrictive and TL-6 the most. The conflicting PL and TL systems existed for several years until the publication of the second edition of the AASHTO LRFD *Specifications* in 1998, at which time AASHTO adopted the TL railing designations.

In an FHWA memoranda issued in 1990 and again in 1997, and in conjunction with the aforementioned changes in crash test criteria, the list of acceptable railings was updated so that as of the 1997 memorandum 74 railing systems had been crash tested (“Action . . .” 1997). These systems are listed in an appendix to the 1997 FHWA Bridge Rail Memorandum and include the following types:

- W-beam bridge rail (2 types),
- Thrie beam bridge rail (9 types),
- Metal tube bridge rail (25 types),
- Vertical concrete parapet (25 types),
- F-shape concrete barrier (4 types), and
- Timber bridge rail (9 types).

Because of the various railing design criteria that have existed through the years (*NCHRP Reports 230* and *350*, AASHTO *Guide Spec*, and LRFD *Specifications*), and the various times that individual rail systems were introduced, a correlation matrix was established for the previously tested rail systems to indicate accepted equivalencies between the various test requirements. The FHWA indicated in 1996 that railings tested under the specifications cited in *NCHRP Report 230*, the *Guide Spec*, or the LRFD *Specifications* will be accepted as meeting *NCHRP Report 350* standards as described in Table 4.

Because of the numerous crash-tested systems now recognized by the FHWA, there is significant flexibility in selecting the appropriate railing design for a project. Typically, states will have standard railings that have been subjected to the crash testing requirements of one of the aforementioned reference standards. However, latitude is provided to select alternate systems, some of which are open rails, have special aesthetic detailing, and range from low-cost to expensive systems depending on the railing design and means of attachment.

Bridge rails can be an expensive component of a project whether from a new construction or a bridge rehabilitation perspective. Owing to the cost of the railing and the various functions the rail serves (structural, functional, aesthetic, etc.), care should be taken when selecting the appropriate railing.

OFF-SYSTEM BRIDGE TYPES—CURRENT PRACTICE

This section explores the types of off-system bridges currently being constructed and presents results from the project survey and the literature search. Information concerning off-system bridge types comes from the literature, information provided by bridge product manufacturers, electronic sources, and personal contacts made by the study team. The project survey collected opinions and information on many aspects of off-system bridge replacements; these responses are presented here.

Superstructure Options for Off-System Bridges

In survey questions BT-1 and BT-2 agency preferences regarding structure type were determined. The agencies were

TABLE 4
BRIDGE RAILING TEST LEVEL EQUIVALENCY (“Bridge Railing . . .” 1996)

Bridge Railing Testing Criteria	Accepted Equivalencies					
NCHRP Report 350	TL-1	TL-2	TL-3	TL-4	TL-5	TL-6
NCHRP Report 230		MSL-1 MSL-2		MSL-3		
AASHTO *Guide Specifications*		PL-1		PL-2	PL-3	

Notes: TL = test level; MSL = multiple-service level; PL = performance level.

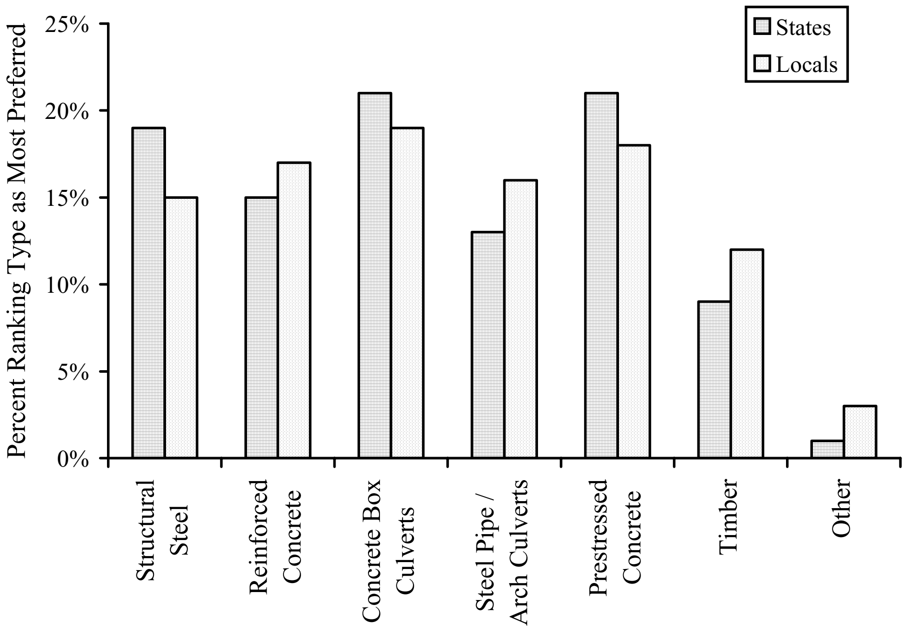


FIGURE 11 Structure type preferences from project survey.

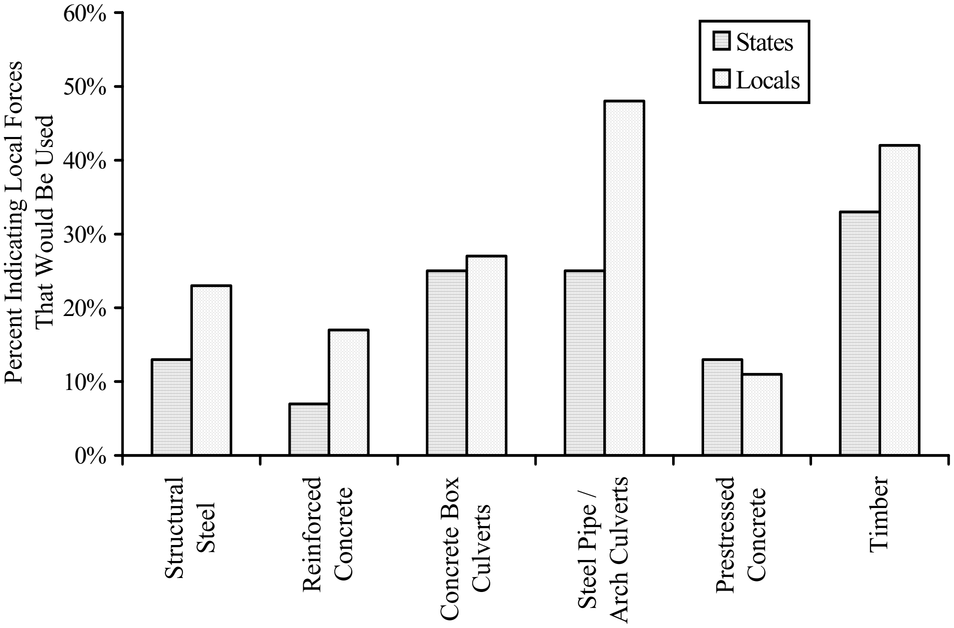


FIGURE 12 Construction capabilities of local forces.

asked whether they would choose or be able to build any of the various bridge types and the reasons for their expressed preference. Their preferences and ability to build various structures with in-house forces are depicted in Figures 11 and 12. In Figure 11, the respondents were asked to rank their choices of structures. The percentages shown reflect the preferences for the various bridge types. In Figure 12, the data presented reflect the percentage of state and local agencies that indicated an ability to build the various structure types with in-house forces. Examining the local agency construction capabilities it is clear that bridges of simple construction requiring minimal fieldwork and small equipment are the structures most likely to be constructed using local agency personnel.

The concrete box culvert is the structure most favored by both state and local agencies responding to the survey. This likely reflects the fairly quick installation time, low cost, ready availability, and durability of concrete box culverts. State agencies prefer materials more common on higher-volume roads, namely structural steel and prestressed concrete structures. Local agencies on the other hand have a greater preference for reinforced concrete and timber bridges and steel pipe arches and culverts.

Initial cost, ease of construction, LCCs, and durability were evenly ranked as the primary reasons for choosing a particular type of structure (Question BT-6). This reflects economic and functional considerations when selecting a bridge type and indicates at least some consideration being given to future problems and maintenance needs. Just behind these four reasons were material availability, familiarity, and ease of design. A small percentage of owners indicated that their choices reflected a lack of competing options.

A separate but related question (BT-13) also inquired as to whether there were geographic reasons for an agency's preferences regarding bridge types. The intent of the question was to determine if regional material availability, historical trends, local construction experience, etc., were considered to be significant reasons for the selection of bridge types. The consensus among both state and agency survey responses indicated that two-thirds of the agencies believe that there are geographic reasons for their choices, and a number of written responses were provided detailing the various geographic reasons for bridge type selection. Geologic conditions as well as local terrain and topography were cited as having an impact on the type of bridge (and presumably foundation types) chosen for bridge replacements. These issues included the presence of hilly topography, which dictates long spans, and steep sites with poor soils that require long bridges and expensive, deep foundations at abutments and piers. Conversely, several responses indicated that very flat terrain dictates short spans and shallow structures to provide adequate hydraulic openings.

Remoteness, the ability to ship large pieces, and the proximity of steel or prestressed concrete fabricators were also frequently mentioned as important considerations. Several responses indicated a preference for prestressed concrete structures because of the inability of local steel fabricators to compete economically. It was also mentioned that the local availability of heavy lift equipment allows for the use of heavier concrete products, limiting some of the advantages of other materials relative to weight and handling.

Regional climate and its impact on bridge maintenance policies were also discussed in the survey responses. Most frequently mentioned were that the local climate, freeze–thaw cycles, and the use of deicing salts were important considerations in the selection of the bridge materials.

In general, the responses illustrated that local agencies are aware of the choices available and those that traditionally perform best in their areas. In some cases, lack of competitive options dictates their choice; however, it appears that lack of options alone is not a problem. Geography, geology, and local agency and contractor experience generally dictate the choice of structure regardless of the merits of some other possible solutions.

Specific questions were posed in the survey concerning bridge deck and railing preferences. A discussion of the responses is presented in the following sections.

Bridge Decks

Because deteriorating bridge decks are such a pervasive problem, the survey sought to determine deck type preferences. These preferences indicated that CIP concrete decks are still the most preferred deck type by state and local agencies. After CIP concrete, the order of preference was full-depth precast and partial-depth precast with CIP toppings. The only difference in responses from state and local agencies was in their order of preference for steel grid or timber decks. A summary of the agency responses relative to deck preference is presented in Figure 13.

The most common bridge deck types continue to be those constructed of reinforced concrete; however, the survey responses also indicated that concrete bridge deck maintenance is one of the most pervasive bridge maintenance problems. A large number of deck problems are associated with older concrete bridge decks that have insufficient cover, unprotected reinforcing steel, or both, among other problems. Most of the deck deterioration problems are the result of cracking that allows for the intrusion of moisture and salts that accelerate the progressive corrosion process.

Some of the responses mentioned the use of shrinkage compensating concrete in concrete deck construction. The Ohio Turnpike Commission (OTC) has extensive experience with the use of Type K Shrinkage Compensating Concrete (SCC), having used it in 520 bridge decks (Phillips et al. 1997). Typically used on steel bridges, either composite or noncomposite, decks have been constructed using SCC since 1984. The OTC has been pleased with the performance of bridge decks constructed using SCC. It should be noted that constructing SCC bridge decks on bridges with concrete stringers is not recommended because of the significant restraint provided by the concrete stringers to shrinkage and thermal expansion and contraction.

Effective use of SCC in bridge decks requires some specific procedures for placing the concrete and curing. Highlights of differences in construction are that SCC typically requires placement by pumping, has a shorter work-

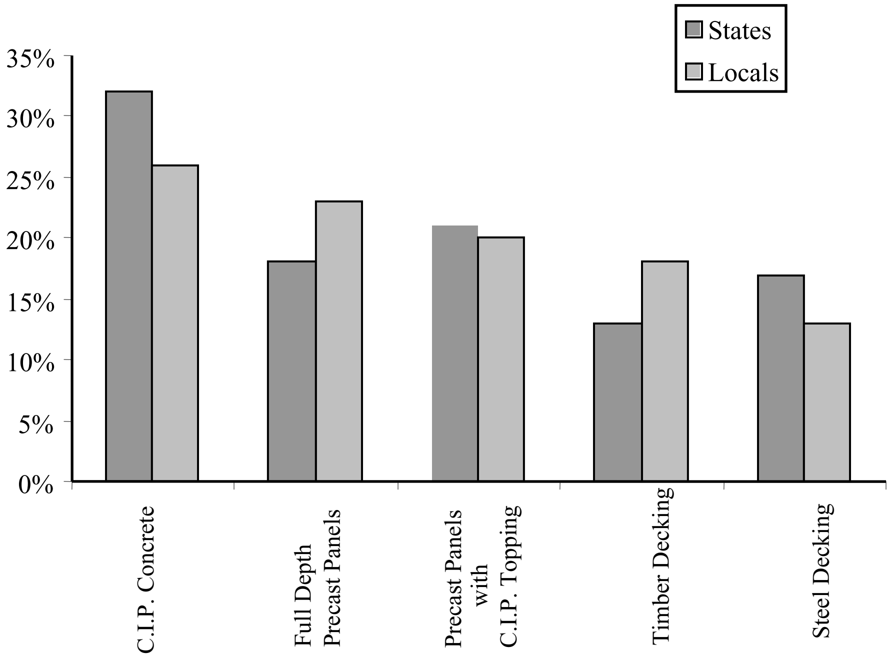


FIGURE 13 Bridge deck type preferences from project survey.

ing time, and must be wet cured with moist burlap for seven continuous days. These and other procedures employed by the OTC are described in the aforementioned reference. A complete description of the specification requirements for SCC bridge decks, a step-by-step description of SCC bridge deck construction, and illustrations of typical construction are also presented.

SCC bridge decks may be an effective solution to bridge deck deterioration problems that essentially plague all bridge decks. They may be considered for the construction of new bridge decks for off-system bridges provided that the more involved construction procedures can be accommodated. The greater complexities in delivering the appropriate quality concrete and accurately constructing and curing these decks may be a challenge for some agencies and the use of SCC decks should be considered with these limitations in mind.

Bridge Railings

The survey requested input regarding the percentage of state and local agencies that use traditional concrete barrier rails (i.e., Jersey barriers), timber railings, steel railings, or no railings at all on off-system bridges. All states responding indicated mandatory compliance with the *NCHRP Report 350* requirements, with 89% indicating that concrete Jersey-type rails were used, and with a similar percentage of respondents (83%) using post-and-beam steel rails. Approximately one-half of the states indicated that they have used timber railing systems.

For the county respondents, the most prevalent is the post-and-beam steel rail, with approximately three-quarters of the respondents reporting its use. Timber railings are used by approximately 42% of responding agencies.

It would appear from the railing survey responses that the concrete railing is much more common on state-owned off-system bridges than on those bridges under local control. There is a clear implication that the Jersey barrier (including rails such as the F-shape) is considered either too expensive or simply “too much railing” for off-system bridges by local agencies. This disparity is likely a reflection of traditional construction practices and state standard rails that are used system-wide regardless of traffic volume. Only half of the local agencies indicated that such railings are used at all, and no information was collected as to how frequently they are used. One of the concerns expressed by a local agency respondent relative to tall/solid railing systems is their tendency to trap snow on bridge decks, which was considered a source of future maintenance problems. Other rail systems (nonsolid) are not as prone to this problem.

A survey of state DOT websites was conducted to determine to the extent possible the types of railings in use by the various agencies and if there were any special railings in use for low-volume or off-system bridges. New York

State has a significant number of approved railings and a variety of choices for off-system bridges; non-NHS structures is their criteria for alternate railings. Examples of railings approved for use on non-NHS structures include thrie beam railings, double box beam curbless railings, timber railings for longitudinally laminated timber decks, timber rails on concrete decks, thrie beam transitions to timber rails, and standards for upgrading numerous existing bridge railings.

The majority of information in the literature regarding bridge railings for low-volume or off-system bridges comes from research sponsored by the USDA FPL. There is minimal information in the literature outside of that sponsored by the FPL programs.

Substructure Options for Off-System Bridges

In general, this project focused on superstructure-related issues. This is a reflection in large part on the amount of literature available with respect to bridge superstructures versus substructures. Substructures however are a very important element that should be addressed to the extent possible. Although they are not as prone to maintenance problems as superstructures, when substructures do have a problem it is typically an expensive problem and one that is difficult to remedy. For new structures, the choice of substructure type has a profound impact on structure cost. This is especially true in locations where deep foundations are required owing to unsuitable soil and rock conditions or concerns with scour. The construction of bridge substructures should be appropriate for the site, focus on durability and stability, and pose minimal maintenance problems.

Various options for abutment construction exist. The most common and most preferred by both state and local agencies is CIP concrete, with states expressing a much stronger preference for this type of construction. However, other options, such as soldier piles and lagging, sheet pile abutments, and pile bents are used and considered more favorable by local than by state agencies. Abutment type preferences are presented in Figure 14, where the percentages reflect the relative preference of each type when owners were asked to rank the various choices.

A similar question was posed regarding pier type preferences (see Figure 15). Again, CIP concrete structures were the option most favored by both state and local agencies, but with a greater affinity for pile bent structures by local agencies.

In general, regarding substructure types, there is much less of a spread from the most to least favorable substruc-

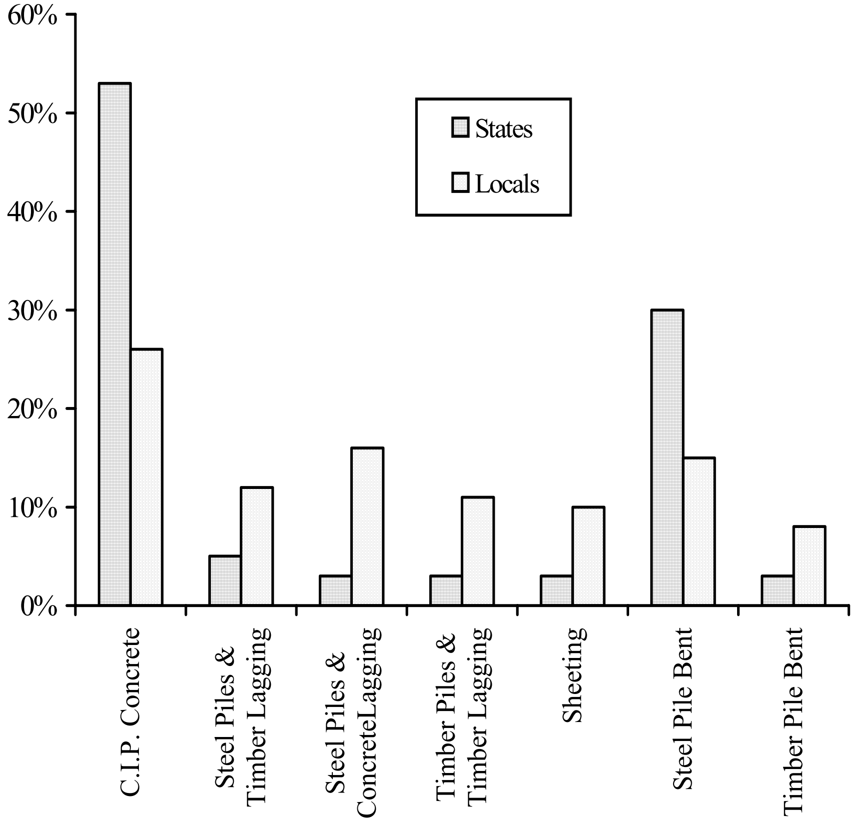


FIGURE 14 Relative preference of abutment types.

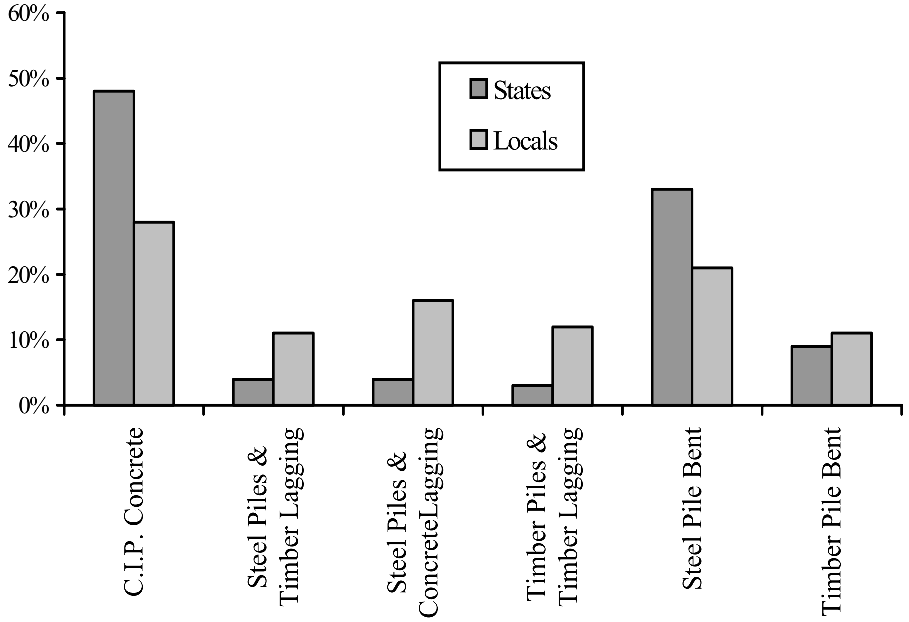


FIGURE 15 Relative preference of bridge pier types.

ture types for both abutments and piers for local agencies. This again may be a reflection of limited state experiences with many of the proposed substructure types. Counties may have more experience with various substructure types and therefore a greater tendency to more evenly rank the alternatives.

Another aspect of bridge substructure construction is bridge scour. Because of various problems with spread footings in scour prone locations, it is generally advised that except for the case of sound rock not prone to scour, footings should be founded on deep foundations. Agencies were specifically queried about this issue in survey question BT-10 to ascertain the percentage of agencies that construct footings on deep foundations when required because of scour potential. The responses indicated that 81% of the time for states and 73% of the time for local agencies footings on deep foundations are required except when footings can be founded on nonerodible rock.

Several inferences can be drawn from these percentages. One could infer that scour prone footings continue to be constructed (i.e., from responses less than 100%), which is certainly undesirable from the perspective of problems with safety and maintenance. The other inference is that spread footings are being constructed, but that the footings are protected in some other way such as by placement of riprap, sheeting, streambed paving and protection, lowering of the bottom of footing, or alternate means. Many of these protective measures, although used as maintenance solutions, are generally not considered to be permanent scour countermeasures as described in the FHWA Report *Bridge Scour and Stream Instability Countermeasures, Experience, Selection, and Design Guidance*, 2nd edition (2001). The types of scour countermeasures used by state and local agencies are presented in Figure 16. The percentages presented in the figure reflect how many of the responding agencies have used the individual types of scour protection.

Prefabricated Bridge Systems

One of the areas of interest for this synthesis was the experience and opinions of bridge owners relative to the use of prefabricated and pre-engineered bridge systems or bridge components. Because of the simplicity of construction of some of the prefabricated concepts, the availability of "off-the-shelf" engineered bridges, and the lack of engineering and construction staffs in small agencies, it was anticipated that the use of prefabricated and pre-engineered bridge products would be looked on favorably by local bridge owners. When asked to rank in order of importance their reasons for using prefabricated and pre-engineered bridges or bridge components, bridge owners provided the responses shown in Figure 17.

Both state and local agencies indicated essentially the same ranking of reasons for the use of prefabricated and pre-engineered products. Of interest is that the reasons for selection are essentially the same as those given for site-built bridges. Cost, ease of construction, traffic considerations, and durability are the primary reasons for selecting manufactured products, with inadequate staff or other options ranked last as for site-built bridges. It was anticipated that the lack of engineering staffs would be a greater "selling point" for these types of systems and that the savings

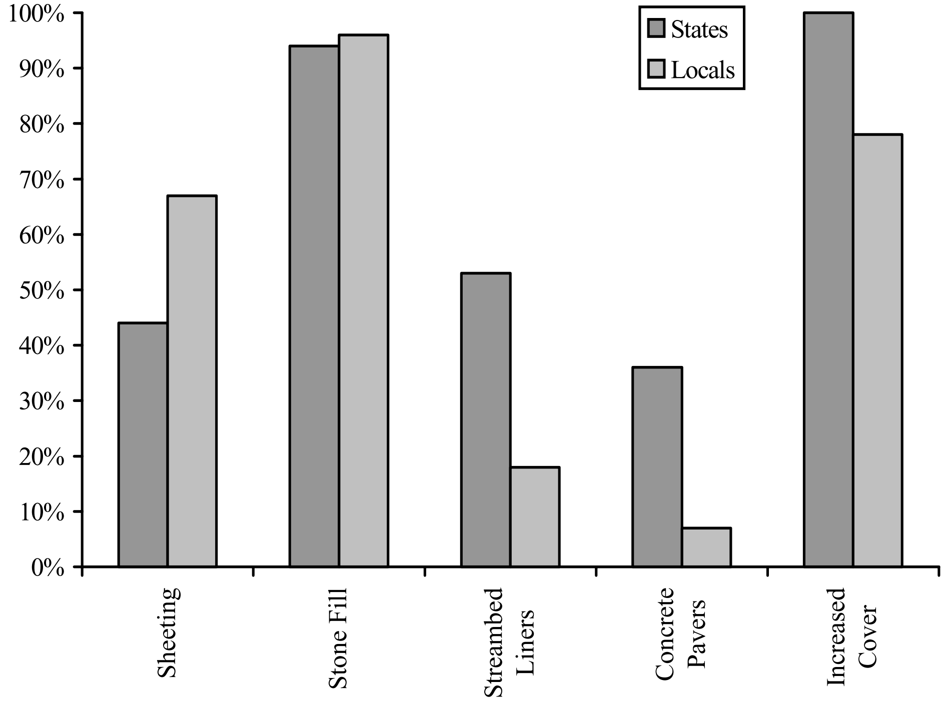


FIGURE 16 Scour countermeasures employed by survey respondents.

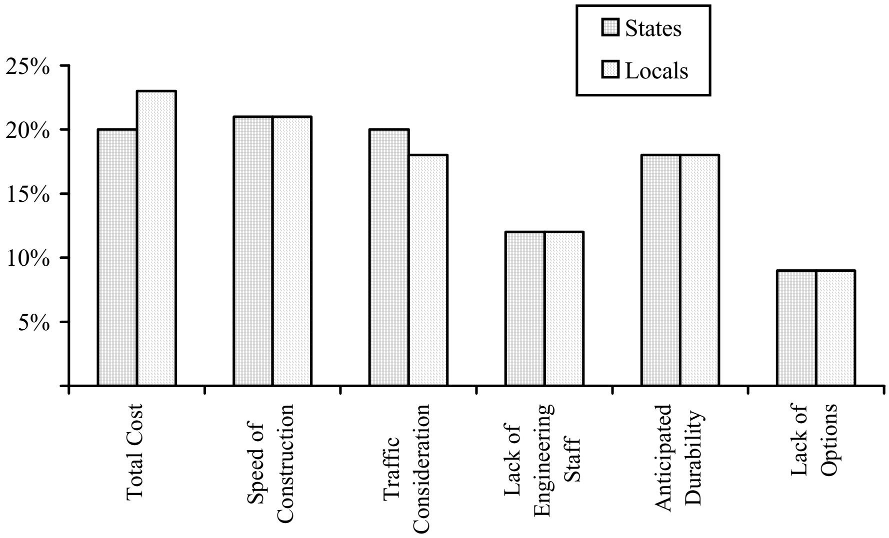


FIGURE 17 Prefabricated bridge system use survey response.

garnered by not having to procure engineering services would have a positive economic benefit. The survey responses do not indicate such a perceived problem or benefit relative to engineering. There is also the possibility that such systems are simply underutilized and that the potential benefits are greater than currently realized.

State and local agencies were requested in survey question MR-2 to consider the use of pre-engineered (and usually prefabricated) bridge components. With regard to the consideration of pre-engineered decks, 39% of state and 43% of local agencies indicated that such systems are considered. A larger difference exists relative to pre-engineered bridge replacements, with 72% of state and 55% of local agencies considering the use of such products.

Concerning the actual products in use, a large number of responses were provided and various systems were discussed. A number of responses indicated the use of products produced by local maintenance staff, whereas most others describe the use of locally produced commercial products. A short synopsis by material type is presented in the following paragraphs.

Precast Concrete Products

Almost all of the survey responses cited the use of a precast or precast/prestressed product of one kind or another. The generic options include the use of I-beams; box beams; solid slabs; T-beams, including double- and quad-stemmed members; pipe and precast box culverts (single and multi-cell); American Society for Testing and Materials (ASTM) standard culverts; three-sided open-frame culvert structures; bridge deck panels; and channel beams. One of the local agencies responded that they prefabricate their own reinforced concrete bridge beams, 0.9 m wide by 0.4 m deep (3 ft wide by 16 in. deep), for use in bridges with spans of up to 9.5 m (31 ft). These beam slabs are designed for MS 22.5 (HS 25) loading, and are supported by county-built abutments and constructed at a cost of 50% to 70% of that if completed by a contractor. In addition to the generic products described, various proprietary products were also mentioned.

Prefabricated Metal Products

In contrast to the precast concrete products, where most of the options cited were for beam-type structures, the structural steel prefabricated bridge options generally fall into two categories: trusses and pipe/arch culverts. The majority of the systems mentioned are trusses. The other commonly cited solutions were corrugated metal (steel and aluminum) pipe culverts and structural plate arch structures. In addition to these commonly cited solutions, corrugated steel decking and steel and aluminum grid decks were mentioned.

Timber Products

The responses noting timber structures came almost exclusively from local agencies. Various types of products were mentioned, such as laminated timber decks, glulam timber panel bridges, nail-laminated timber panels fabricated by local forces, glulam- and dowel-laminated bridge caps, railings, and decks.

BRIDGE REPLACEMENT OPTIONS FROM THE LITERATURE

In this section, some of the standard and innovative solutions that exist for the replacement of off-system bridges and found in the literature are presented. These solutions may consist of the use of traditional materials and construction techniques, innovative materials, time-saving construction techniques, use of standardized solutions requiring little or no design, or combinations thereof. As a result of the combination of limited budgets and bridges that are generally small to medium in size because of their location on off-system routes, nontraditional structures and techniques may be expected to be more prevalent off-system than on more heavily traveled highways. Administrators of off-system bridges need to find ways to reduce the expensive engineering and construction costs typical of normal design and construction processes while still obtaining durable, safe structures. The use of innovative solutions is one way in which this can be accomplished.

Prefabricated Bridges

There is a significant amount of information in the literature concerning the use of prefabricated bridge products. Prefabricated products include everything from the ordinary, such as precast concrete I-beams and rolled steel shapes, to the more innovative products, systems, and assemblies that can be used to expedite construction and provide a long life. The application of some of these concepts is presented in the following sections.

Prefabricated Concrete Bridges

Concrete is the most common material prefabricated for bridge construction. Whether using short-span precast reinforced concrete elements or precast and prestressed concrete elements, the use of concrete is most closely tied to prefabricated bridges. A description of some of the findings relative to the use of prefabricated concrete bridges follows.

The development and load testing of a short-span bridge concept using precast double-T beams transversely post-tensioned through the slabs for load distribution is discussed in Shahawy (1990). The concept is additionally innovative in that a CIP topping is not required; the precast flanges form the riding surface. The edges of the precast slabs (of the double-T sections) are slightly beveled so that a CIP closure joint can be poured to join the adjacent sections. Post-tensioning is then applied to create a transversely continuous section. The bridge type was developed as a combined effort of the Florida DOT and local precasters and is an effective bridge replacement concept for spans of up to approximately 20 m (65 ft). Although longer spans may pose handling or shipping problems, it is anticipated that the system can be used on spans of up to 24.4 m (80 ft). The experimental testing of the bridge system is described in the aforementioned reference.

Conclusions of the research and load testing of half-scale models as well as proof-load testing of two prototype structures constructed in Tallahassee indicated the following. Transverse post-tensioning to create an average stress of 1034 kPa (150 psi) across the longitudinal joint was sufficient to ensure adequate fatigue life of the longitudinal grout joints and to ensure proper joint shear strength. An average stress of 2068 kPa (300 psi) is required at the ends of the beams to strengthen the free ends of the slabs and eliminate the need for end diaphragms. Live-load distribution for this system is accurately predicted by the standard AASHTO formula S/1.676 (S/5.5). A combination of straight and draped strands gave the best performance. A savings of approximately 15% was realized in the construction of the first prototype bridges owing to reduced erection time and the elimination of a CIP slab or topping.

In response to a need for cost-effective shallow structure alternatives to CIP continuous concrete slab bridges, an inverted tee (IT) girder system was developed and is discussed in Mounir and Tadros (1996). The lightweight precast units have a high span-to-depth ratio, are relatively easy to fabricate, and require minimal fieldwork. The intended applications of the system are in rural environments where erection of heavy units or long construction times are not feasible, in new construction where superstructure depth must be minimized and conventional forming and construction are not practical, and in superstructure replacement situations where greater spans or load capacities are required, but with comparable depths.

As developed by the University of Nebraska and the Nebraska Department of Roads, the IT system is available in various girder depths ranging from 300 mm (12 in.) to a maximum of 900 mm (35 in.). When used in simple-span construction, the maximum span of the 900-mm (35-in.)-deep section is approximately 34 m (110 ft). The girders may be made continuous either before or after casting the deck, extending by several meters the span capabilities. The girders use a standard bottom flange form, 600 mm (24 in.) wide and variable web sizes to achieve the various section depths. A total of 22 prestressing strands are accommodated in the bottom flange and welded wire fabric is used for shear reinforcing. The girders are placed side-by-side but not connected together mechanically. The short slab span can either be formed with traditional formwork that cannot be recovered afterwards or the void between adjacent beam webs can be filled with an expanded polystyrene. The precast beam concrete has a specified strength of 51 MPa (7,500 psi) at 28 days and 41 MPa (6,000 psi) at release. The deck concrete is 34 MPa (5,000 psi) at 28 days. The heaviest precast element, the 900-mm (35-in.)-deep section, weighs 4.87 kN/m (334 plf) and thus is light enough to be easily transported and erected.

Following testing to validate the section strength and overall behavior, the Nebraska Department of Roads adopted the IT system as a standard for new or reconstructed bridges. The system has been successfully used on projects in Nebraska as well as in Iowa, Kansas, and Florida. With regards to economics, a study of the construction costs of a three-span continuous concrete slab bridge compared to an IT system bridge was conducted. It was found that the IT superstructure was 20% less expensive than the slab alternative. Because of longer span capability, additional savings are possible owing to a reduction in the number of substructure units required.

Several proprietary precast concrete bridge replacement systems are described herein. Discussion of these systems is not intended to be an endorsement or an expression of preference for these structures over other suitable products. The discussion is intended to illustrate the options available for large-scale precast concrete structures, describe some typical installations, and discuss the pre-engineered aspect of the products.

The Bebo system of precast concrete arch bridges is a product intended for bridge replacements over streams and small roads. A complete product package, as well as a CD-ROM including design and installation information, is available (Bebo 2000). Available in various spans from 3.6 to 25.6 m (12 to 84 ft), the arches come in several forms. Circular arch bridges are produced with spans of between 9.1 and 12.8 m (30 and 42 ft) and rises of between 3.5 and 8.1 m (11.5 and 26.5 ft). The hydraulic areas of these sections are large, but come with a high-profile structure. An alternative to the circular arch shapes is elliptical shaped arches. These arches have span capabilities of up to 25.6 m (84 ft) with relatively flat span-to-depth ratios. For spans of up to 14.6 m (48 ft) the structure is a single-piece arch, whereas for longer spans the structure is precast in two halves, which are connected in the field with a CIP closure joint. The arches are typically designed for MS 22.5 (HS 25) loading, but can be designed for special live loads if necessary. The standard arches can accommodate fill heights of 0.5 to 4.6 m (1.5 to 15 ft).

The structures are generally easy to construct, with only small spread footings (grade beams) or pile-supported grade beams in the case of poor soil conditions. Once the footings are constructed, the arches are erected on the footing against each other to form the desired roadway width. No post-tensioning or mechanical connection is required between adjacent sections. Depending on the span of the arch, the length of the segments ranges from 1.2 to 2.4 m (4 to 8 ft) to limit their weight and to simplify shipping and handling. In addition to the standard precast concrete arch rings, precast spandrel walls and wingwalls are also used. The spandrel wall, arch ring, and wingwalls interlock and support each other; final stability is only attained following backfilling, which is separated into three zones. Because the arches require interaction between the structure and soil to derive their capacity, only well-draining backfills (granular soil groups A-1 through A-4) with low plasticity are acceptable. Backfilling should generally be done symmetrically on both sides of the arch to balance the lateral loads; layers should be placed and compacted in layers not exceeding 0.3 m (1 ft). The hydraulic capacity of all of the Bebo structures is computed in accordance with FHWA HEC-5, *Hydraulic Design of Highway Culverts* (1985).

In general, little needs to be done by a local agency interested in installing a Bebo span. The products are pre-engineered, and simple input forms are completed by the agency for the precaster so that the appropriate structure can be fabricated. Additionally, a complete hydraulic evaluation is performed to ensure that hydraulic conveyance is adequate.

Costs for the system were provided by the manufacturer, Rotondo Precast, a division of Oldcastle Precast, for a series of structures in Pennsylvania and Ohio. The prices quoted include the arch, spandrel walls, wingwalls, and other required construction materials for arch construction. Typical costs are also included for plant engineering preparation, shop drawing, and hydraulic evaluation, along with delivery and erection of the precast pieces. Backfilling and paving are not included in the following costs.

- Bridge 1: 12.8 m span x 21.3 m roadway width (42 ft x 70 ft), Pennsylvania
- Cost = \$190,000 (\$700/m^2, \$65/ft^2).
- Bridge 2: 7.3 m span x 16.6 m roadway width (24 ft x 54 ft), Pennsylvania
- Cost = \$60,000 (\$495/m^2, \$46/ft^2).
- Bridge 3: 12.8 m span x 46.9 m roadway width (42 ft x 154 ft), Ohio
- Cost = \$405,000 (\$674/m^2, \$62/ft^2).
- Bridge 4: 14.6 m span x 65.8 m total width (48 ft x 216 ft), Pennsylvania
- Cost = \$385,200 (\$401/m^2, \$37/ft^2).
- Bridge 5: 9.1 m span x 30.8 m roadway width (30 ft x 101 ft), Pennsylvania
- Cost = \$205,000 (\$731/m^2, \$68/ft^2).

The other similar product described here is the Con/Span system (Con/Span n.d.). Although similar in concept to the Bebo system, there are some differences in shape and span capabilities between the two. The Con/Span structures are three-sided, open structures with natural bottoms. The lowest portion of each "arch" is composed of straight-sided walls, while a series of compound circular curves forms the balance of the sides and roof of the structure. Con/Span structures come in a range of spans from 3.6 to 14.6 m (12 to 48 ft) and rises ranging from 0.9 to 4.3 m (3 to 14 ft). For long spans, the arches can be placed in a "daisy chain fashion," creating multiple openings across the channel. The arches may also be placed on pedestal walls to increase their conveyance or vertical underclearance. Like the Bebo system, the Con/Span structures use precast spandrel walls and wingwalls, but with different proprietary details. No post-tensioning is required between adjacent units. The standard design load is MS 22.5 (HS 25).

Details on the construction and backfilling are provided in this paragraph. The units are typically set on a strip foundation with a keyway and grouted to the footing following their placement. Backfilling is strictly controlled in the critical backfill zone because of the need for soil–structure interaction. The requirements are generally similar to the Bebo system in that backfill classes of A-1 to A-4 are acceptable. The fill must be placed symmetrically up both sides of the arch to balance the lateral earth pressures. A series of charts are provided in the Con/Span design manual for determining the strip footing size as a function of arch span, cover height, design live load, and allowable bearing pressure. Lateral thrust is also computed for the various design cases. Sample design calculations are provided for determining the reinforcing required in strip footings.

There are several approaches presented for the Con/Span system of hydraulic capacity. A free program is available for determining inlet and outlet control depths using FHWA culvert analysis procedures. Additionally, the FHWA HDS5 and HY-8 procedures are applicable for analysis. The waterway area and wetted perimeter for culverts running full or at various partially full depths are given. Capacity curves relating culvert size, headwater depth, and discharge, "Q," are given for the standard products. If the structure is to be used in a HEC-RAS, HEC-2, or WSPRO analysis, geometric coordinates to define the structure opening are also provided.

The Con/Span manual provides details on the construction of skewed and curved structures made from the standard elements. The faces of the elements are typically beveled to accommodate the skew and/or curve. A number of project profiles are provided illustrating various applications of the systems. Reports of successful load testing and engineering research are presented at the end of the manual.

Several projects where precast arch systems have been used are described in the following paragraphs.

Hurd (1996) described the replacement of a deteriorating bridge in Erie County, New York. Originally the plan was to replace the existing structure with another steel girder and concrete deck bridge. The new bridge was to be built on a parallel alignment, would involve a stream realignment, would close the existing road for an entire season, and was estimated to cost \$1.1 million. Concerns were raised during the environmental review about the stream realignment and the impact of the long process on the trout stream. Additionally, state requirements were such that because of the new alignment, the bridge would have to be designed for a 100-year storm, whereas if the bridge alignment was maintained, the new structure would only have to convey flows similar to the existing bridge. The ability to build on the same location was seen as a positive because it would substantially accelerate the environmental permitting process. It was also important to construct the new bridge over the summer. Thus, an easily constructed solution was required.

An accelerated and innovative schedule was used for procurement and construction. The county decided to contract directly with the precaster so that fabrication could begin earlier than the traditional design–bid–build procedure would allow. Only general layout drawings were initially available for precasters to bid on by May 1. The actual construction contract was not awarded however until July 6. Site work, including bridge demolition and grading, began in mid-July and the site, including footings, was ready by early August when the precast arches arrived. A total of eight 12.8 m (42 ft) span arches were used side by side to form the new bridge. The units are 1.2 m (4 ft) wide, have a rise of 3.5 m (11.5 ft), and weigh approximately 18 t (20 tons) each. The units were placed with a 227-t (250-ton) hydraulic crane. All eight arches and precast spandrel walls were unloaded and erected in a single day. The job was finished ahead of the September schedule, which earned the contractor early completion incentives.

An even more aggressive schedule is described in Hurd (1998). In this article, the replacement in five construction days of a deficient bridge serving a major limestone quarry is described.

When the only bridge leading to the quarry had its rating reduced as a result of deterioration, access to the quarry was eliminated. The county indicated that programming, design, and construction of a new bridge could take up to 5 years, which was not acceptable to the quarry owner. The quarry owner reached an agreement with the county to replace the bridge on their own. Design, hydraulic analysis, and preparation of construction drawings were done for the quarry owner. The plans were reviewed by the county, which also assisted with utility relocation, guardrail installation, and other maintenance activities in support of the construction. The old bridge, only 7.3 m (24 ft) wide was replaced by a wider structure with a 13.4 m (44 ft) roadway width and 8.5 m (28 ft) span length.

The production of the precast elements for the new bridge (14 arch sections, 2 precast spandrel walls, and 4 precast wingwalls) took 3 weeks. Total construction was completed in 6 days and included a weekend shutdown of the road.

This bridge included several firsts for Monroe County, Ohio. It was the first time a private business paid directly for a bridge replacement, the first precast arch bridge installation in the county, and the first time there was a precaster representative onsite for the duration of the job.

Hurd (1997) also discusses the use of precast concrete arches to replace a functionally obsolete and extensively deteriorated multi-span arch bridge in Chicago. The bridge carries four lanes of city traffic over pedestrian paths connecting portions of Garfield Park. The existing arch bridge was considered to be an appropriate architectural design, therefore a replacement arch was preferred; however, cost was a significant concern. To minimize costs, precast arches were specified so that a low profile could be maintained, thus eliminating any grading work and minimizing foundation construction. Speed of erection was also an important consideration; therefore, the elimination of time-consuming CIP construction was a primary reason for selecting a precast product.

Designed for AASHTO MS 18 (HS 20) loading, three spans measuring 8.5 m (28 ft) each were specified with a rise of 2.4 m (8 ft). Eight sections per span measuring a total of 14.6 m (48 ft) wide were used to build the desired width for four traffic lanes. Instead of granular fill over the arches, the city chose to specify concrete fill to improve ride quality. Precast wings were used on the bridge approaches, retaining a typical granular fill. Because of the aesthetically sensitive location of the bridge, architectural cladding panels were installed on the exterior arch sections along with ornamental lighting, parapets, and reconstructed sidewalks.

Construction began in November 1995 with the removal of the old bridge. Following shipment of the precast arches [445 km (275 mi)] from the precast plant, erection of the arches took only 1 week. Following arch erection, the various architectural features were installed and the extensive site improvements completed. Construction was finished at a total cost of $1.2 million. The project was designed by Chicago DOT engineers and was largely constructed by DOT crews with funds provided by the city and state. The cost of the structural precast concrete was $171,900 and the total project cost, including demolition, aesthetic treatments, and all related site work, was $1,690/m^2 ($157/ft^2).

Chiou and Slaw (1998) discussed the replacement of a 1920s vintage CIP reinforced concrete arch in Somerset County, New Jersey, with a precast concrete replacement structure. The objectives of the replacement were to maintain the architectural character of the original crossing, minimize environmental impacts to the stream below, complete the bridge within strict budget and time constraints, and minimize disruption to traffic in the adjoining downtown area.

The replacement structure is a precast concrete arch having a clear span over the stream of 18.3 m (60 ft), a total length of 27.4 m (90 ft), a rise of 2.9 m (9.5 ft), and an out-to-out width of 15.2 m (50 ft). To facilitate casting, shipping, and erection of the arch the structure was precast and erected in halves, with a CIP closure joint at the crown. The arch halves were supported on falsework shoring towers during the casting operation. The precast arch sections measured 356 mm (14 in.) thick and 2.36 m (7.75 ft) wide. The appearance of the old bridge is maintained by precasting fascia panels that resemble an older earth-filled spandrel arch bridge. Additionally, precast and CIP elements are used in the bridge railings, which have the appearance of older open baluster rail types.

The use of precast elements was important in minimizing the construction time and thus the impact on local traffic. The total construction time was approximately 2.5 months, with a total cost of $775,000. The bridge was deemed a success by local officials who indicated that similar structural concepts would be considered for bridge replacements in the same span range.

For a number of years, the construction of new or replacement bridges in the form of single- or multi-cell culverts has been a popular choice. The project survey conducted for this synthesis indicated that culverts are the most commonly used bridge for off-system applications for those situations in which their use is appropriate. To help standardize the design, fabrication, and construction of culvert structures, the ASTM maintains a standard (ASTM C1433/1433M) for precast box sections.

The ASTM standard includes a number of predesigned box culvert sections to accommodate the AASHTO MS 18 (HS 20) loading, Interstate loading, or various earth loadings. Standard culvert designs are presented for single-cell box structures as large as 3.66 x 3.66 m (12 x 12 ft) with earth cover up to a depth of 5.5 m (18 ft). The required concrete strength and reinforcing size and spacings are presented for all of the design scenarios. A search of various precaster websites indicated that the culverts commonly available around the country include the standard ASTM designs. The ready availability of such sections, their standard design, and almost universal acceptance makes them an attractive choice for small-to-medium-size stream crossings provided that a sufficient number of boxes are used to accommodate anticipated flows.

Prefabricated Steel Bridges

Prefabricated steel bridges are not as common as precast concrete structures. They are typically available in some form of truss configuration. Although prefabricated trusses are usually associated with temporary "Bailey Bridge"-type applications, other types of trusses are available for temporary or permanent installations. Additionally, a prefabricated steel bridge system using traditional multi-stringer construction is described later.

A number of fabricators of prefabricated bridge trusses were identified during the conduct of this synthesis, including Acrow and U.S. Bridge. There are other truss manufacturers, and the mention of these two is neither an endorsement nor a statement of preference.

The Acrow Panel Bridge is a descendant of the Bailey Bridge developed as a rapid bridge replacement system for military use during WW II. The bridge has three general components, all of which are stock items assembled as required to form bridges of various sizes. The truss is composed of a standard truss panel measuring 3 m (10 ft) long, 2.2 m (7.2 ft) high, and only 0.16 m (6.5 in.) wide. Numerous panels are joined together to create bridges of varying lengths. Maximum spans of 70 m (230 ft) are available in configurations that support up to three lanes of MS 22.5 (HS 25) live load. With some restrictions in the number of lanes and/or live loading, simple span designs are tabulated for spans up to 76 m (250 ft). To accommodate these heavy loads and long spans, multiple trusses are used side-by-side. Although very long spans can be achieved, the standard trusses for off-system replacements are likely to be much shorter. Spanning between the trusses are similar standard floor beams. The common decking is a prefabricated orthotropic panel that spans longitudinally between the floor beams, although other decks such as wood or steel grid can be accommodated. The system can either be used in thru truss or deck truss configurations. Truss top chords are stable in thru truss configurations and do not need lateral support. All components are galvanized for weather resistance.

The following is a case study that illustrates the rapid delivery and installation of the Acrow system. After a fire closed Interstate 80 in New Jersey, disrupting the flow of 130,000 vpd, an Acrow bridge was installed as an emergency replacement. Only 17 h after the New Jersey DOT provided the notice to proceed, the bridge had been designed, and standard components assembled and trucked to the job site. Several additional 24-h days were needed to demolish the old bridge and install the replacement span. Although similar traffic demands are not common on off-system bridges, the simplicity of design, fabrication (assembly of pre-existing parts), delivery, and erection are important features. The system could be used to replace washed-out stream crossings following a flood, as a temporary bridge while a permanent structure is built, or for the permanent replacement of deficient bridges.

The U.S. Bridge system is similar to the Acrow system in that prefabricated trusses are used; however, the method of fabrication and construction is significantly different. Whereas the Acrow system uses small prefabricated panels, sometimes several panels wide, and is field bolted to form a crossing, the U.S. Bridge system is primarily an all-welded truss system. The only bolted connections on the truss are where the prefabricated truss panel assemblies are joined in the field. Depending on the bridge size, several panels of the truss are welded together using conventional W-shapes for the truss members. The entire assembly is hot dip galvanized to a coating thickness of 7 mils, which is greater than the ASTM required thickness. A 35-year warranty is provided for the coating. Alternate materials such as weathering steel or painted trusses are available, but the standard product is a galvanized truss.

The trusses are available in standard lengths of up to 46 m (150 ft) and in various widths up to three lanes wide. The trusses are through type with either parallel chords or, in the case of the longer spans, a curved top chord or "camelback" configuration. The trusses may be designed to accommodate sidewalks and utilities. The typical deck system uses underslung floor beams or floor beams, simply supported stringers, and a deck system of galvanized corrugated deck pans supporting asphalt fill. Other decks such as traditional concrete-filled pans or timber decks are permitted and can be accommodated.

A U.S. Bridge company representative was interviewed for this synthesis to ascertain their impressions of the off-system bridge market from the perspective of a supplier. The intent of the interview was to learn their perspective on bridge replacements for low-volume and off-system bridges. One of the issues raised was the difficulty that local agencies have in procuring replacement structures for existing deficient bridges in a quick and efficient manner. Several examples were cited where a prefabricated truss was supplied and paid for with 100% local funds and the total cost was less than the local agency 20% match for a "DOT compliant" bridge. The typical locally funded bridge might be a single-lane bridge designed for MS 18 (HS 20) loading and reusing existing substructures. A new structure that would be considered eligible for matching funds would be a much wider bridge on new substructures and might have additional environmental and right-of-way costs that increase the price above what the local agency feels is appropriate for a particular location. The long process of getting a local bridge on the State Transportation Improvement Program (STIP) and obligating the local match funds was cited as a significant impediment.

It was mentioned in the course of the interview that new trusses, or in some cases trusses removed from another location, rehabilitated, and supplied to a new owner, were substantially less expensive than other "conventional" replacement options. It was mentioned however that often states are reluctant to accept types of bridges that are not among the typical bridges they construct.

The use of welded thru truss bridges to replace deteriorated structures is described by Heine (1990). The author discusses the process that Albany County, New York, used to replace a number of bridges using bond funds and county engineering and construction employees to execute the work. The availability of county workers and the ability to reuse some of the bridge substructures were important considerations that led to selection of the steel truss bridge replacement. Owing to limitations in contract price that restrict the amount of work the counties can do themselves, a portion of the bridge construction was contracted out, specifically truss erection. However, a crew of six county maintenance personnel with experience in carpentry or masonry rehabilitated the existing abutments and backwalls, set new bearings, performed approach pavement work, and installed guardrails.

The counties biggest concern was for an effective bridge replacement for low-volume one-lane roads, some carrying as little as 50 vpd. For approximately $120,000, the county was able to replace two single-lane bridges using all-welded A588 steel, chosen for its maintenance and aesthetic considerations, and designed for an MS 22.5 (HS 25) capacity. This included the cost of all materials, erection, and the cost of the timber deck. The cost for the bridges averaged approximately $538/m^2 ($50/ft^2), whereas conventional bridge replacements are priced as much as six times higher. The total time from the closing of the old bridge through demolition, substructure rehabilitation, and construction of a new bridge was approximately 2 months, as compared with as much as 8 months determined for bridge replacements using other types of structures. For another example of the use of prefabricated steel truss bridges refer to the portion of this chapter on Bridge Recycling.

The Inverset system is a prefabricated steel bridge system with potential uses for off-system bridges as well as broader application for bridge replacements in general (Fort Miller 1995). Patented in the 1980s, this is a prefabricated bridge that takes advantage of composite action and the use of rolled shapes to create prefabricated bridges that can be used in single- or multi-span applications. The most innovative feature of the system is the method of fabrication.

For rolled shapes in particular, there is a significant amount of the section that is inefficiently used. This is because of the symmetric nature of the beam and the large compression flange. The Inverset system was developed to increase the efficient use of the beams and also create more durable decks. The casting sequence involves creating a grid of the longitudinal stringers and intermediate diaphragms with the entire unit fabricated upside down. The slab is cast using formwork, which is hung from the beams. This method of construction produces compression in the eventual bottom flange and tension in the eventual top flange, contrary to normal construction techniques. Once the slab cures, a crane is used to invert the entire unit. The resulting condition is similar to shored composite construction; however, it has the additional benefit of the stringers being partially prestressed by the weight of wet concrete. Final stresses at erection are near zero in the bottom flange, are tensile in the top flange, and are compressive in the slab owing to the inversion. The net compressive stress in the slab increases slab durability as it delays the onset of deck cracking. By having zero stress in the tension flange under dead load, the section is much more efficiently used for live loading, the dominant load in short-to-medium-span bridges. The net result is that either heavier design loads can be carried per stringer, as compared with a typical field-cast unshored structure, or smaller stringers can be used than in typical construction. Greater efficiency can be obtained either way. Additional external prestress load in addition to self-weight can be applied to the system during casting, resulting in even greater stringer efficiency.

A typical unit consists of two stringers spaced at a desired distance with cantilever slab projections of 0.45 m (18 in.). The units are placed adjacent to each other in the field, connected with diaphragms; the overhanging slabs, which have keys cast in their exposed edges, are grouted together with nonshrink grout. The combination of a fixed overhang distance with user-specified beam spacing results in uneven beam spacing in the completed bridge. Grid analysis and experimental load testing have shown that the live-load distribution is more efficient than the AASHTO formula of S/1.676 (S/5.5) for typical interior stringers in multi-beam bridges. Various skew, horizontal, and vertical curvature alignments can be accommodated in the casting process. Additionally, the units can be used in multi-span construction, with compression or strip seals at the piers and abutments, or can be made continuous for live load by casting a field closure pour that engages the ends of sequential units in adjacent spans. This method is analogous to that used to construct prestressed concrete structures poured continuous for live loads. Jointless bridges can also be constructed with these units. Finally, they also can be used to replace a deteriorated floor system in a truss or through girder bridge with the elements spanning transverse to the direction of traffic.

The design guide for the Inverset system includes a design example of a typical single-span bridge, discussions of the various options for meeting project-specific geometric constraints, lists shipping and installation procedures, and details the typical materials and construction features used with regard to anticipated durability. Regarding installation and erection requirements in particular, the width and length of typical units results in crane picks that are manageable with readily available equipment. In the example bridge, three units, each weighing 24 800 kg (55 kips), are required to be erected to complete the entire bridge, which has a total width of 7.9 m (26 ft) and a span length of 16.8 m (55 ft). A single crane is typically used for loads of this size, although the bridge could be slid from one abutment to the other on slider beams and lifted at each end with two smaller cranes. A typical installation is described as requiring a crew of five or six, with the delivery, rigging, lifting, and placing of each unit taking only approximately 1 h. Shorter times are possible depending on logistics and site constraints.

Two innovative prefabricated steel bridge concepts are explored in Wipf et al. (1994). The systems described have been successfully used by county engineers in Iowa, as well as in other countries.

The first concept is known as the beam-in-slab (BIS) system. The BIS concept is somewhat of a hybrid between a conventional steel beam bridge and a solid concrete slab bridge. In the BIS bridge, typical steel-stringers span between the abutments at a spacing of approximately 0.6 m (2 ft), with span lengths of up to 12 m (40 ft). The exterior stringers are typically channel sections with the flanges turned inward. Once the beams are set, plywood is placed between the bottom flanges for formwork and the void space between beams is filled with concrete up to the level of the top flanges. No reinforcing is placed in the slab. Typical beams used to date have been W-shapes with nominal depths ranging from 250 to 300 mm (10 to 12 in.). The BIS system results in longitudinal stiffness and strength contribution from both the steel and concrete. The depth of the bridges is minimized because the "slab" is level with the beam tops. The system also allows for the use of recycled beams in a novel fashion. In Iowa, in the early 1990s, costs for these bridges ranged from \$320 to \$430/m^2 (\$30 to \$40/ft^2).

Several modifications to the BIS system were also proposed. Two observations for the BIS system are that with full-depth concrete construction the top of the steel beam is not required to carry the compressive bending forces, because the full-depth concrete is more than adequate for that purpose. Similarly, concrete at the bottom of the section is an inefficient use of material owing to its poor tensile strength. Modifications are suggested to the BIS system to remedy these two shortcomings.

The first modification involves removal of the top flange and portion of the web of the steel beams. If deep enough W-shapes are available they can be split into WT sections. The steel now is used as an inverted T and is only in the lower half of the system. This system can be made to act compositely with the concrete by drilling or torching regularly spaced holes in the beam web so that a concrete “dowel” is formed when the CIP concrete flows through the beam web hole. An additional modification involves the use of the T-beam configuration with reduction of concrete on the tension side of the system. The recommendation is to place a segment of CMP between the flanges, forming a barrel vault or jack arch appearance on the underside of the system. Placement of these pipe sections reduces the weight of concrete significantly and eliminates it from the tension side of the system. The combination of the split-T composite beams and the CMP bottom forms saves significant quantities of steel and concrete with no compromise in strength and may result in higher capacities owing to dead-load reductions.

A variant of the Inverset system was also described. In what was described as “System 1” in the report by Wipf et al. (1995), two steel stringers, new or used, would be cast compositely with a thin concrete deck, 100 mm (4 in.) thick. This could be done by county workers in the off-season. Each unit, of which four would be required for the construction of an 8-m (26-ft)-wide bridge deck, weighs approximately 10 000 kg (11 tons) for a simple span of 15 m (50 ft). These units are easily shipped and placed by simple equipment. To connect adjacent units, steel plates are embedded at the edges of the overhanging flanges of each section. These plates are then welded together in the field much the same way that precast double-T units are in building and parking garage construction. An additional 125 mm (5 in.) of CIP topping is then placed, which acts compositely with the scarified top surface of the precast units. The finished deck resembles a traditional constructed deck.

Prefabricated Timber Bridges

Modern timber bridges are much different than their older sawn-timber counterparts. They typically employ engineered lumber of some form [glulam, laminated veneer lumber (LVL), or parallel strand lumber (PSL)], are connected for enhanced load distribution and performance (by use of spreader beams or transverse post-tensioning), and are almost universally pressure treated for enhanced durability. Additionally, they are largely prefabricated. Examples include the use of prefabricated timber slabs for use in slab-on-beam construction, longitudinal slabs for use in short-span bridge replacements, glulaminated rectangular beams for multi-stringer construction, LVL or PSL T-beams or box beams, and other novel forms such as glulaminated arches for longer spans.

The development of modern timber bridges has been significantly advanced in the past 15 years by the Timber Bridge Initiative and its successor the Wood in Transportation Program (WIT). These programs have produced numerous design aids for timber bridges, developed specifications and standard design procedures for various forms of sawn and engineered timber, and promoted the development of modern timber bridges. Additional outgrowth of the programs has been an extensive database on the field performance of various timber structures including load test results. One of the other areas advanced by the timber bridge set-aside programs has been in the area of timber bridge railings for use on timber and concrete deck bridges. These railings come in various configurations and have been tested to different crash test levels. Information on many of these developments is readily available. The single most comprehensive resource for information on timber bridge design, construction, and performance is a CD-ROM including approximately 220 electronic documents (*Information on Modern Timber Bridges* . . . 2001). Several references included on this CD as well as other sources of timber bridge information are discussed in the following paragraphs.

Brungraber et al. (1987) discussed the state of the timber bridge population in rural America, as well as the prospects for increased usage of timber bridges as viable replacement options for deteriorating low-volume road bridges. Although the statistics are somewhat dated owing to the time of publication, this report can still provide valuable insights into the problems and challenges of managing rural bridge populations. It also documents the importance of rural roads and bridges on the overall economy.

At the time of the publication of the Brungraber et al. (1987) report, there were approximately 65,000 timber bridges in the United States. These bridges were primarily in the midwestern and south-central portions of the United States and not part of the federal-aid system. As of August 2000, NBI data indicated only 34,541 timber bridges, approximately one-half the number only 15 years earlier. This indicates a rapid decline in the number of timber bridges and that these bridges are being replaced by other types of structures despite the many advancements in timber bridge technology during the same time period.

The Brungraber study cites the advantages for modern timber bridges as being logistical, performance, and economic related. Logistic benefits involve the ease of fabrication, shipment, and installation of timber bridges. These are typically small bridges, easily shipped, and installed by small construction crews with average training. Timber bridges can be installed under adverse weather conditions, because temperature extremes have no bearing on construction. Performance benefits include the excellent resistance of timber deck panels to the effects of deicing salts.

The economic benefits of timber bridge construction are site specific and regionally variable. In the midwestern and south-central regions of the United States, where timber bridges have an established base, their economics are a tangible benefit, whereas in high traffic areas such as the Middle Atlantic states, they are not a prevalent bridge type. Another economic advantage is that owing to their light weight they can be used on old substructures and be more readily fabricated and installed by local workers. One of the reasons cited for their lack of use and economic disadvantage in some areas can be attributed to a lack of familiarity or the assumption that timber bridges are of the old vintage that have proven to be problematic.

The replacement of a short-span bridge in Connecticut is discussed here as a cost study of the economics of modern timber bridges. For both the timber and steel options, the material costs were within several thousand dollars of each other; however, the timber bridge was constructed with local workers, thus saving an additional $20,000 over the cost of the steel alternate. The installed cost of the timber bridge option was $40,000. It should be noted that by using local funds (i.e., no federal matching funds) the town was able to circumvent the mandatory AASHTO compliance. The estimated cost of an AASHTO-compliant structure was $400,000, with the town's 20% share equaling $80,000 or twice the amount it spent to fully fund the replacement with local funds. Brungraber et al. (1987) cited a U.S. General Accounting Office study that indicated the wide disparity in prices between locally funded and matching fund projects is common, the implication being that the mandated process, including reviews, elevated minimum design loads, use of contractor labor, etc., significantly inflates the total construction costs.

An examination of the underlying reasons for the past poor performance of timber bridges is presented in Smith and Stanfill-McMillan (1996). A survey of timber bridge perceptions and performances was conducted in four states: Mississippi, Virginia, Washington, and Wisconsin. The objective of the research was partly to examine whether the high percentage of timber bridges considered deficient was the result of the performance of the timber itself or for other reasons, such as roadway deficiencies, waterway inadequacies, or substructure conditions.

The survey concluded that timber bridges have a perceived inadequacy when compared with other types of bridges. However, when considering the respondents, state DOT officials, state DOT engineers, and local highway officials, the highest ratings for timber bridges come from local officials. Analysis of the NBI data for the four study states indicated that Mississippi had the greatest number of timber bridges as well as the most deficient timber bridges. The state does not have a standard design process or standard plans for timber bridges. The same can be said of Virginia and Washington. The only state with standard design plans for timber bridges among the study group was Wisconsin. The perception and documented performance of timber bridges in Wisconsin is much better than in the other surveyed states. More than 80% of Wisconsin's timber bridges have a satisfactory rating, which the authors imply is largely the result of the use of standard design rules and plans.

In general, the performance of timber bridges was demonstrably better for structures on state and federal road systems than for those on local roads. This again is believed to be because of a lack of consistent design standards for off-system, locally owned bridges and variable maintenance on these bridges. Timber stringer bridges are the most common type of timber bridge and are largely deficient, whereas timber slab bridges, the second most common, are considered satisfactory more than 85% of the time. Analysis of the source of the rating of timber bridges as structurally deficient (SD) indicates that poor performance of the deck or superstructure is the reason that timber bridges are considered SD only 11% of the time. This is the best combined percentage of all the materials studied. Low SD ratings for timber bridges are primarily from substructure deficiencies (20%) and from inadequate structural or waterway capacity (39%).

In states with no timber bridge design standards, the vast majority of bridges are designed for live loads of MS 13.5 (HS 15) or less, and in many cases the design load is unknown. More than 90% of the bridges with these low design loads in Mississippi, Virginia, and Washington are considered deficient. Conversely, in Wisconsin, the only state with standards for timber bridges, the satisfactory ratings of timber bridges are excellent, with the satisfaction rating for bridges designed for less than MS 13.5 (HS 15) being 61% and for bridges designed for at least M 18 (H 20) at 94%. This implies a very strong correlation between eventual performance as judged by NBI criteria and the existence of minimum design standards.

Ritter et al. (1996) reported on the design, construction, and testing of several LVL T-beam bridges, with details provided for six separate structures. The LVL T-beams are made of thin wood veneers [individual laminates measure between 2.5 and 6.4 mm thick (0.10 to 0.25 in.)], where the individual veneers are all oriented in the same direction and then glued together to form a completed beam. LVL T-beams can either be fabricated in a single T-shaped section (these shapes can also be formed using PSL) or can be fashioned into a T-section by placing slabs between adjacent solid rectangular beams and transversely post-tensioning the entire assembly together. Instead of the deck resting on top of the beams it is compressed between the tops of the beam webs.

By the early 1990s, approximately 20 of these bridges had been constructed in the Midwest and western United States. One of the obstacles to greater acceptance was the lack of AASHTO standards (which have now been developed) for the design of such bridges. The objective of the Ritter et al. study was to assess the performance of some of the existing bridges. The bridges ranged in length from 7.9 to 13.4 m (26 to 44 ft) and had widths ranging from 4.9 to 11.4 m (16 to 37.5 ft). Beam sizes depended on the particular application and box beams were used as fascia stringers on two bridges to improve their stability. The bridges were similarly transversely prestressed with high-strength steel rods, were pressure treated, and, with one exception, had asphalt wearing courses. Evaluation of the six bridges indicated that the structures were performing well; there was no observed deterioration, although there was a slight loss of prestressing. This was not significant enough to compromise the performance of the bridges.

Based on the successful development of the LVL T-beam bridges, similar prefabricated beams have been developed using PSL technology. The PSL beams start first with thin veneers, but than are again split into thin fibers. These fibers are then aligned longitudinally and pressed, with adhesive, into rectangular billets. The billets are then assembled with adhesive into T-shaped beams of various width, depths, and overhanging flange dimensions. Standard designs use fabricated elements measuring 0.6 m (2 ft) wide; depth depends on span length. Pre-engineered designs are available for beams up to 20 m (66 ft) long and for up to MS 22.5 (HS 25) loading.

Wacker et al. (1997) discussed the design and construction of a timber box beam bridge in Spearfish, South Dakota. The box beam bridge was composed of glulam timber webs, whereas the top and bottom flanges were composed of multiple vertical-sawn lumber elements stacked next to each other. The southern pine glulam webs and ponderosa pine sawn-timber flanges [made of nominal 50 x 150 mm (2 x 6 in.) timbers] are first glued together into modules having three webs and two interior flanges each. The modules are then post-tensioned together to form a continuous unit. The completed bridge measures 19.8 m (65 ft) long, 11.9 m (39 ft) wide, and the boxes are 800 mm (31.5 in.) deep. A total of six prefabricated modules were used to build the entire bridge. Superstructure construction was completed in a single day including bar stressing. The bars were retensioned 3 and 7 weeks following construction owing to the relaxation of the bars and creep of the timbers. Loss of bar force has continued to be a problem for this bridge, and it has been retensioned two additional times, 1 year and 3 years after completion. It is hypothesized that this is the result of moisture loss in the sawn-timber flanges and stress relaxation in the timbers. This is not unusual for stressed timber bridges and can be corrected with periodic checks with retensioning as necessary. The bridge has been load tested and its behavior is linear elastic, and measured deflections and overall performance are as expected.

As a response to the limited resources available to Iowa's 99 counties for local bridge replacements, research was undertaken to demonstrate the feasibility of using locally available timber resources, in this case pressure-treated cottonwood, in the construction of economical bridge replacements. The concept of exploring the use of local native materials in timber bridge construction is an outgrowth of the Timber Bridge Initiative enacted by the U.S. Congress in 1988. The construction and testing of several solid deck cottonwood bridges constructed in southern Iowa is discussed in Lee and Ritter (1997). In general, several years after construction, the bridges were found to be in good condition, and load test results are consistent with the performance of stress-laminated bridges made of other species. The broader conclusion is that native materials of various timber species and grades can be adapted to the design and construction of engineered timber bridges for county bridge replacements. The inexpensive local materials, coupled with county labor crews, result in inexpensive total bridge costs and those that maximize the availability of many local resources.

An extension of the Timber Bridge Initiative Program is the reconfigured WIT Program (Cesa et al. 2001). The WIT Program has three main goals: (1) demonstration projects, (2) research, and (3) technology transfer. The demonstration project portion of the program is directed at promoting economy of scale as opposed to the funding of novel but limited application concepts. By focusing on economy of scale and refinement of concepts to a commercial status, the broader objective of developing a sustainable class of bridge construction is furthered. With annual budgets for the WIT Program of less than $2 million per year for 1996 to 2000, there was limited opportunity to fully fund projects. The resources are redirected toward the commercial projects, where the USDA Forest Service assists local entities in the design of structurally adequate and economical structures whose objective is to demonstrate the viability of wood as a transportation material. Examples of commercial projects include the replacement of several similar bridges where the same engineers, contractors, material suppliers, etc., are involved in all bridges. Cesa et al. (2001) discussed three such projects.

Yellowstone County, Montana, a largely agricultural area, needed to replace three WW II-era bridges with structures capable of sustaining a high volume of highway design truck loads. The bridges had spans of 11.9 m (39 ft) and roadway widths of 7.6 m (25 ft) and were designed for AASHTO MS 18 (HS 20) design live loads. The alternatives were either conventional glulam beams or beams reinforced with fiber composites. The conventional beams were selected. In addition to the conventional glulam beams, timber pilings, abutments, and rails were also used on the project. The cost for each bridge was approximately \$87,500, or \$495/m^2 (\$46/ft^2), and the largest piece lifted weighed approximately 1360 kg (3,000 lb). The WIT Program contributed $100,000 toward the total cost of these three bridge replacements.

Ida County, Iowa, received a $124,500 grant from the USDA WIT Program to fund the replacement of five deficient bridges using locally available cottonwood. Four of the bridges use cottonwood decks on recycled salvage steel stringers, whereas the fifth is an all cottonwood structure. The bridges were designed and mostly constructed by county road crew personnel. This was the first time these crews had constructed a new bridge. The structures ranged in length from 8.8 to 14.3 m (29 to 47 ft), had a roadway width of 7.3 m (24 ft), and were designed for AASHTO MS 18 (HS 20) design live loads. The abutments consisted of gabion baskets filled with stone installed by county employees. By using recycled steel beams, the cost of the bridges was kept low, with the cost for the first bridge being only $61,539, or $287/m^2 ($26.70/ft^2).

In West Virginia, several bridges that were neither maintained nor claimed by any agency were allowed to deteriorate to the point where essential commercial traffic was restricted from some areas. This prohibited the passage of fire vehicles, heating fuel trucks, and parcel services, and had a direct economic impact on fire insurance rates. In 1998, as a response to this problem, the West Virginia Division of Highways began a program of adopting “orphan” roads. With an estimated 3,200 orphan roads totaling 1238 km (769 mi), a large number of bridges required replacement. These bridges have an average length of 7.6 m (25 ft) and an average width of 4.3 m (14 ft). West Virginia has used plank timber deck or nail-laminated decking on steel beams as a common replacement. No wearing surface is used, a timber curb is provided as the railing, and the abutments are typically stone-filled gabions. The bridges are constructed by DOT maintenance personnel in less than 1 week at an average cost of less than $25,000.

These three commercialization projects demonstrated a concept used several times, so that lessons can be learned, economics of scale realized, and various deficient structures remedied.

In addition to research into timber bridge systems, extensive work has been carried out in the area of developing low-cost crash-tested bridge railings made from timber or for use on timber bridges. Some of this work is described in the following paragraph.

As of 1990, a total of 47 bridge railings had been successfully crash tested and approved by the FHWA for use on federal-aid projects, only one of which was for attachment to a timber deck. Recognizing the trend toward crash-tested railing systems, Ritter et al. (1995) and Faller et al. (1999) summarized several years of development of cost-effective crash-tested railing systems intended for use on longitudinally and transversely laminated timber deck bridges.

In Ritter et al. (1995) the research objective was to develop five crash-tested rails, three meeting the AASHTO PL-1 criteria, one meeting the AASHTO PL-2 criteria, and the fifth meeting the *NCHRP Report 350* TL-4 criteria.

With the given criteria, attachment, post, and rail details were developed for the identified scenarios. All of the systems have several common features, particularly the means of attachment to the deck. The attachment of the post, which is outside of the deck and not on top of it, consists of treaded steel rods inserted through bore holes in the deck and anchored some distance away from the edge of the deck in a routed pocket.

For the PL-1 criteria, the three rails developed consisted of two all-timber options, a timber rail and timber post with a curb and a timber rail with timber post without a curb, as well as a W-beam post with spacer block and steel thrie beam railing. All three rails were tested successfully to the specified test criteria. For the PL-2 level, a single-rail system was tested, essentially a slightly strengthened version of the thrie beam railing tested at the PL-1 level. Some localized stiffening and strengthening was all that was required to upgrade the railing to the PL-2 level. Finally, the TL-4 railing was a timber railing system with upgraded posts, railing section, and additional attachments through the curb section connecting the curb to the bridge deck. Costs for the PL-2 steel railing and the glulam TL-4 railing are also presented. The steel thrie beam railing material costs $174/m ($53/ft), whereas the glulam timber railing material costs were $354/m ($108/ft). Additionally, both vehicle repair costs and anticipated repair costs were higher for the glulam railing.

The results of this testing indicated that cost-effective crash-tested railings exist for timber bridge structures. The PL-1, PL-2, and TL-4 crash-tested rails discussed are those that appear in the *Plans for Crash-Tested Bridge Railings for Longitudinal Wood Decks* published by the FLP of the USDA (Ritter et al. 1995a).

Faller et al. (1999) summarized the development of 11 cost-effective crash-tested railing systems intended for use on longitudinally and transversely laminated timber deck bridges. For longitudinal wood decks, nine crashworthy rails were developed, five of which were described previously. The additional four railings included three tested to the TL-1 level and one tested for low-volume forest roads at a level below the test requirements for TL-1. For the transverse panel bridge decks, two rail systems were tested to the TL-2 level and an additional two to the TL-4 level. For the development of all of the railings, glulam decks were used as the base structure.

Faller et al. (1999) discussed the aforementioned PL-1, PL-2, and TL-4 railings, as well as additional railings developed for a TL-1 level for longitudinal laminated decks and four railings for transversely laminated decks.

Subsequent modification of the same railing systems, but for attachment to concrete decks, was done. These modified details are published as *Plans for Crash-Tested Wood Bridge Railings for Concrete Decks* (Ritter at al. 1998).

A study by the USDA Forest Service documenting the costs of timber bridges constructed from 1989 to 1995 is presented by the National Wood in Transportation Information Center (Coole 1996). At the time the report was prepared, cost data for 112 vehicular bridges were available, and more than one-half of the bridges were from three states, West Virginia (46), Pennsylvania (10), and New York (9). The remaining bridges were scattered throughout 23 other states, with no state reporting costs for more than four bridges. Costs were broken down by structure type, bridge length, and species.

With respect to structure type, the least expensive bridge type is a dowel-laminated structure that costs \$473/m^2 (\$43.97/ft^2), followed by LVL/PSL T-beam bridges with an average cost of \$475/m^2 (\$44.15/ft^2). The next least costly bridge types are longitudinal glulam bridges with an average cost of \$512/m^2 (\$47.57/ft^2). The cost of stress-laminated deck bridges is \$549/m^2 (\$51.07/ft^2), followed by transverse glulam decks over glulam stringers at a cost of \$570/m^2 (\$53.02/ft^2). The most expensive bridge types are stressed box and stressed T type bridges with costs of \$697/m^2 and \$733/m^2 (\$64.83 and \$68.18/ft^2), respectively. Cost by structure type indicates that the dowel-laminated bridges and structures using LVL and PSL lumber are the most cost-effective.

Costs per unit area were also compiled for bridge sizes, specifically, bridge lengths. For bridges in excess of 15 m (50 ft) in total length, approximately one-half were simple spans. Single-span bridges had an average cost of \$736/m^2 (\$68.41/ft^2), whereas the multi-span bridges, which required an intermediate bent, were significantly less expensive at \$459/m^2 (\$42.64/ft^2). The least expensive bridges, excluding the multi-span bridges in excess of 15 m (50 ft) total length, were those with a total length of from 7.6 m (25 ft) to 9.8 m (32 ft), whose total costs averaged \$565/m^2 (\$52.50/ft^2). Shorter and longer bridges had greater costs, with average costs of approximately \$669/m^2 (\$62/ft^2). The data tend to indicate that timber is economical for short spans and when used as a series of simple spans in multi-span continuous construction.

Finally, the ranking of bridge costs with respect to species are, from least to most expensive, Douglas fir, ponderosa pine, red oak, southern pine, red maple, red oak/southern pine, and finally northern hardwoods. The data indicate a strong trend toward the cost-effectiveness of western softwoods. Additionally, considering all factors (bridge type, size, and species), timber bridge costs are less in the Northwest than in the East or South, although the sample size in the Northwest is small compared with the East, where the vast majority of the timber bridges have been constructed.

Bridge Recycling

An important "tool" employed by bridge owners and maintenance crews is the concept of bridge recycling. Frequently, as part of a reconstruction project, many structurally sound bridge components can be saved. Various components (bridge beams or trusses, deck components, railing hardware, bridge bearings, etc.) can be saved, rehabilitated, and reused in either already known locations (i.e., planned recycling) or simply stocked for a "rainy day." With budget constraints and the innovative thinking of county maintenance departments, bridge recycling can have a significant impact on local bridge populations.

Approximately two-thirds of the state and local agency survey responses indicated that stockpiling and reuse are performed in their jurisdictions. Many different components were listed as being recycled including the mundane, such as bridge drains, to the salvage of entire bridges, typically truss bridges. The most frequently cited elements were bridge decks and deck panels, bridge and approach railings, and superstructure beams (steel, concrete, and timber). Several responses indicated that the recycled components are intended for future use in other bridges, whereas others use the salvaged elements for falsework and shoring on future jobs. There were several responses that indicated that component recycling is not possible because disposed items from construction become the property of the contractors who use these materials as shoring and falsework on their own projects.

The use of recycled bridge deck components removed from the Golden Gate Bridge in 1986 is discussed in Barnts et al. (1994). In response to the need for six bridges crossing Miners Creek in Roseville, California, the city, its engineer, and a contractor developed a plan that reused deck panels removed from the Golden Gate Bridge. A number of constraints existed for the project, mostly environmental related to the salmon that migrate on a seasonal basis. The bridges carry a multi-use trail, but were also designed to carry heavy maintenance and emergency services vehicles. They were required to be low cost, present minimal intrusion into the stream, and be able to sustain significant storm and flood events. With many agencies in the building process, including the U.S. Army Corps of Engineers (USACE), California Department of Fish and Game, U.S. Fish and Wildlife Service, and U.S. Environmental Protection Agency (EPA), minimizing impact was of paramount importance.

The engineer and project developer initially considered recycled bridge components, with recycled railroad products being considered first. However, boxcar frames were not suitable for the loads and piggyback car frames were perceived to cause a debris accumulation problem in event of high water. Additionally, precast concrete deck spans were considered to be too expensive for this application. The solution was the use of salvaged deck sections, 15.2 m (50 ft) long and 2.9 m (9.5 ft) wide, weighing approximately 22 680 kg (25 tons) each. These sections were cut to fit the various required configurations, typically 7.6 m (25 ft) long. Concrete and reinforcement samples were taken from the panels to check their strengths, and the capacity of the panels was determined to exceed the required 178 kN (20 ton) requirement.

Construction was completed in an environmentally sensitive manner with all heavy construction equipment kept out of the streambed. The city was able to complete the project on time and budget at a total cost of $302,000. The environmental agencies were pleased with the minimally invasive construction made possible through the use of recycled bridge products and the speed of construction, as an aggressive deadline was placed on the project relative to fish spawning seasons. The use of recycled products saved several weeks on the work schedule.

Muskingum County, Ohio, also used the concept of bridge recycling as well as pre-engineered and prefabricated bridges to rectify several problem bridges in the county ("Muskingum County Gains a Bridge Plus Four" 2000). A severely rusted four-span steel truss carrying ADT in excess of 5,000 vpd needed to be replaced. The solution was to use an all-welded galvanized thru truss in a three-span configuration [each span approximately 40 m (130 ft) long] built adjacent to the existing bridge so as to maintain the flow of traffic over the river.

So that the bridge could be accommodated in galvanizing kettles, the truss was welded in three large sections, dipped, and field-bolted at only the splice locations in the field. The stringers and floor beams were also galvanized. The deck consists of metal deck pans filled with bituminous paving material.

The recycling component of the project was that once the new bridge was opened to traffic, the existing four-span truss was disassembled, evaluated, cleaned, and rehabilitated as required, and hot dip galvanized. The existing four spans were then disbursed to four separate bridge locations in the county. The county was provided a warranty of 35 years on both the new and old bridges. The total cost of the new bridge was approximately $750/m^2 ($70/ft^2), although in reality the county essentially obtained five bridges for this price.

A variation of the recycling theme is the construction of bridges using recycled components not originally used in bridge structures. In "Canada Puts the Squeeze on Its Trees" (1997), a different type of recycling is described. In Canada, as part of the routine replacement, hundreds of thousands of timber poles are replaced annually. A system has been devised to recycle these discarded poles into bridges for use on low-volume roads.

First, the discarded timbers are trimmed on two opposing sides so that they can be positioned next to each other. The timber poles are drilled so that lateral post-tensioning can be installed, thus creating a transversely stressed log bridge. The post-tensioning is composed of FRP tendons. The stressed log bridges cost approximately $20,000 each, which the authors cite as approximately one-half the cost of typical Canadian bridge replacement projects using steel and concrete. To test the idea of stressed log bridges using discarded utility poles, bridge models were built and tested under laboratory conditions. The quality of the timber in utility poles is superior to sawn lumber and the poles typically have been or can easily be treated with preservatives. The bridge cited in the aforementioned reference (the first of this type) spans 11.6 m (38 ft) and is designed for vehicles weighing as much as 10 metric tons (22,000 lb). Obviously, with the poles having a given capacity, their live-load capacity is a function of the span length. Such a bridge may not be suited for all applications, but the recycling of previously discarded materials into a new bridge structure can be both an environmentally conscious and economically friendly decision.

An illustration of component recycling in the construction of off-system bridges is discussed in Klaiber et al. (1999). Unlike other forms of recycling where various bridge components are removed, stocked, and reused in future construction, Klaiber et al. discussed the use of recycled railroad flat cars (RRFC) for use as bridges.

In that study, it was determined that several states have a fairly large number of such structures. These states are primarily rural, that is, Arkansas, Georgia, Montana, Oklahoma, Texas, and Wyoming. Very little research exists on this topic and only a few literature citations were located, with most of the information coming from questionnaire responses.

Arkansas appears to be the largest user of railroad car bridges, with more than 340 such installations using underbodies from flatcars, gondolas, and boxcars. Arkansas State University undertook a study, discussed in Klaiber et al. (1999), that investigated the practice in Arkansas of railroad car bridge construction. Generally, the most common bridge type is one that uses two cars side by side, with a slight gap between the adjacent cars. The vast majority of the structures reported ranged in span from 6 to 17 m (20 to 56 ft). The Arkansas research also involved load testing of several bridges and comparing the measured response to finite-element predictions for purposes of predicting bridge ratings. The experimental data were in general agreement with the analytical prediction.

California is also a user of RRFC bridge systems as emergency replacements and temporary bridges. The California system uses an upside-down flatcar laid on the ground as a "footing," two halves of a flatcar as "columns," and another flatcar on top of the "columns" acting as a cap. The entire unit is braced to form a temporary bent. These bents are then bridged with several parallel flat cars to create a temporary bridge. This system was successfully used following the collapse of the Arroyo Passajero Creek bridge in 1995, with the exception that the substructure was built as a pile bent. Only 8 days elapsed between the bridge collapse and the reopening of the crossing using the temporary bridge. The cost of the replacement was approximately \$19,000 per flatcar including required modifications. The estimated savings of having the emergency replacement were reported to be approximately \$500,000.

Wyoming has contracted with an independent consultant to conduct tests, including analytical modeling and load rating, on several RRFC bridges. Tests on bridges with relatively deep main girders and significant exterior stringers (connected with tapered floor beams) verified that the bridges can carry legal loads. A third bridge, with shallow interior and exterior stringers and not well connected, rated poorly and is considered to be nonredundant. A conclusion reached in the Wyoming research was that owing to the various configurations of RRFC bridges some basic testing may be warranted to establish the safe-load capacities for a particular installation.

The Montana DOT has the responsibility to inspect and rate the more than 100 RRFC bridges in the state. Lacking the ability to load test all of the bridges, and lacking a systematic approach to load rating, Montana has a three-tiered approach. The most basic approach is to assign a lower bound rating of 4500 kg (5 tons) to the bridge in lieu of other data. Option two involves placing a vehicle of known weight and configuration on the bridge, photographing the load test, and submitting the photos and sketches to the DOT. The DOT will then convert the test vehicle to an equivalent weight Type 3 vehicle and post the bridge for 40% of this converted weight. Option 3 involves the use of an outside engineering consultant who will survey the rail car bridge and determine the load distribution patterns. This includes a field survey of the bridge and material sampling and testing. A structural analysis is then conducted to ascertain the load capacity.

Klaiber et al. (1999) also discussed the development of commercially available RRFC bridges. One company in Redwood City, California, has installed several hundred RRFC bridges on private and low-volume public roads. The bridges are retrofit, if necessary, to carry at least AASHTO minimum loadings as well as exceptionally heavy off-road vehicles used in logging industries. The company indicates that the light weight, ease of installation, ease of maintenance, and long life lead to savings of 30% to 70% as compared with the cost of traditional bridge replacements. The light weight, in some cases, also allows for the reuse of existing substructures.

Component Stockpiling

Component stockpiling is different from the storage of old items for potential reuse described in the previous section and involves the stockpiling of new bridge components for the rapid replacement of damaged structures. Components could either be commercially available items such as precast concrete products, steel I-beams, or H-piles, or could include locally constructed items.

The construction of short-span bridges using precast components manufactured and erected by county personnel is discussed by McLin (1990). Borrowing from a concept developed by the Oklahoma State University extension services, the Daviess County, Indiana, Highway Department built a set of forms that allows them to manufacture small bridge units in pieces that can then be assembled in the field to various widths.

The bridge system involves the precasting of a series of double-T units, 430 mm (17 in.) deep, 1055 mm (41.5 in.) wide, and 7.3 m (24 ft) long. The precast units are then bolted together at the third points using a 25-mm (1-in.)-diameter all-thread rod. Additionally, the top flanges of the double-Ts are notched to allow for the pouring of a shear key in the field. The units, which are designed for an AASHTO MS 18 (HS 20) loading, have been used in side-by-side applications for to a bridge width of up to 7.3 m (24 ft). The outside beams are specially modified to allow for the installation of guiderails.

The units themselves are lightweight, approximately 5200 kg (5.75 tons), thus allowing for their casting, movement, and erection using small equipment owned by the county. County bridge crews can construct the 450 kg (1,000 lb) rebar cage for each unit in approximately 2 h. The cage is tied on a table and lowered into the steel forms. Each beam requires approximately 2.1 m^3 (2.75 yd^3) of 24 MPa (3,500 psi) concrete.

Because construction of each unit is simple and inexpensive, the county can cast units during winter seasons or other down times in anticipation of scheduled or emergency bridge replacements. Additionally, because of the quick turnaround time for casting, these units are an attractive option compared with commercially precast or prestressed concrete products.

The county expense for labor and materials for this system was less than $4,000 (in 1990 dollars). This is compared with $10,000 for an equivalent, commercially produced prestressed concrete system. Several thousand dollars of initial set-up costs were required to build the form and a level pad for tying rebar cages and pouring concrete. Savings from the construction of the first two bridges paid for these set-up costs. In 1990, the county had 100 bridges that were candidates for replacement using this system.

Innovative Materials

One of the means for enhancing an agency's ability to potentially leverage dollars expended for bridge maintenance, rehabilitation, and replacement is through the use of advanced materials. Though typically at the expense of high initial costs, there are some instances in which on a first-cost basis the materials are competitive and also instances that when considering LCCs the materials are cost competitive. Some of the materials and applications can still be considered experimental or in their infancy. There are yet to be answered questions concerning true long-term field performance of some of the materials and additional issues regarding the lack of standardized design, fabrication, construction, and inspection procedures. However, what is known from laboratory testing and a growing number of field trials is that these materials appear to have many desirable characteristics that make them attractive as bridge replacement alternatives.

A portion of the funding for a number of the various applications of emerging technologies currently being used in highway rehabilitation and bridge replacement comes through the FHWA Innovative Bridge Research and Construction (IBRC) Program. Authorized as part of the Transportation Equity Act for the 21st Century (TEA-21) legislation, the IBRC program provides a nominal amount of funding, $1 million per year for the 6-year TEA-21 authorization, for research into innovative materials, and a total of $102 million over the same period for construction activities. Because of the innovative nature of the projects, the goal was to fund as many of the projects as possible with a 100% federal share; however, the actual federal expense is at the discretion of the FHWA. The funds can be used to cover engineering, rehabilitation, and construction costs for bridges on any public roadway, and may also be used for proprietary products provided the proprietary nature of the product is clearly identified. The monies may only be used to offset the innovative features of the project. To qualify for IBRC funds, a project must meet one of the following criteria:

- Development of new cost-effective innovative material highway bridge applications,
- Reduction in maintenance or LCCs including the costs of construction,
- Development of construction techniques that increase safety and minimize disruption,
- Development of engineering design criteria for innovative materials,
- Development of innovative and cost-effective measures to separate vehicular and railroad traffic,
- Development of bridges more apt to sustain the effects of natural disasters, and
- Development of new nondestructive evaluation methods.

Each year the FHWA requests proposals for projects from the states, which in turn may coordinate with local agencies to identify locations where an innovative solution may be appropriate.

Although the IBRC is a limited source of funds, a large number of projects are funded every year in some part, because the monies are only used to offset the delta costs associated with the use of the innovative materials. Many of the projects funded under the IBRC program use advanced composite materials, innovative metallic reinforcing steel blends for enhanced corrosion properties, and materials such as high-performance steel and concrete for use in bridge construction.

FRP Products

There are two common applications for FRP materials in new bridge construction, the construction of all-FRP slab bridges and the construction of FRP decks for use with stringers composed of traditional materials. The decks may be constructed of various materials, but are generally made of either glass- or carbon-based fibers bound with a resin.

Cassity (2000) presented a brief overview of the characteristics of FRP deck units used in construction at that time. Although still a small market in terms of the number of bridges constructed or rehabilitated, FRPs currently have promise as niche materials and may have the potential for more widespread use as alternatives in the bridge rehabilitation and replacement fields.

The most common type of bridge deck systems, whether used as deck panels over conventional stringers or in slab bridge configurations, are composed of glass fibers and polyester or vinyl ester resins. These decks are available in two common configurations, pultruded tubes and sandwich systems. In almost all cases, both types of decks are prefabricated and adhesively joined together in the field. The decking units are typically coated with an overlay for skid resistance and durability. The overlays may be conventional latex-modified or high-density conventional concrete, although these overlays do not have stiffnesses and strengths compatible to those of the FRP. More appropriately, a thin polymer-modified overlay is used. Hot asphalts have also been tried.

When used as traditional decking units over stringers a haunch of a traditional grout material must be built. Whether or not the deck is made to act compositely with the stringers, a nominal amount of shear connection must be used to prevent differential movement between the two elements and deterioration of the haunch concrete over time. Composite action, if desired, can be obtained using conventional shear studs for steel beams or shear stirrups in precast concrete beams; however, there will be the added expense of forming pockets in the FRP deck system.

The analysis by Cassity (2000) and by an independent engineering firm indicated that the initial cost of an FRP deck system is two to three times that of a conventional concrete deck system and these initial costs must be balanced with savings in life-cycle or construction costs. When prefabricated FRP decks are used, costly construction delays can be avoided on high-volume roads because of reduced construction time. This savings in construction time may be just as important for rural roads. Although the number of vehicles is not the driving factor behind the speed of construction, remoteness of the site and the criticalness of keeping a given bridge open, such as for emergency services, may be just as important if not more so.

Cassity and the engineering firm found that FRP decks used in multi-beam bridges had LCC saving of 10% to 30% over conventional decks for a 75-year design life. This is primarily the result of reduced user costs for both initial construction and rehabilitation and repair procedures.

In addition to their use in multi-stringer bridges, FRP decks are also a viable option for the redecking of truss bridges that originally had concrete or open-grid decking. Older trusses may be controlled by weight limitations and the reduced mass of an FRP replacement deck (20% of the weight of a concrete deck) may allow for increased load capacity, thus eliminating the need for posting or other limitations. Additionally, the closed deck provides protection of the truss floor system that an open deck grating does not, thus reducing maintenance costs associated with deteriorated floor beams and stringers in trusses.

Cassity asserts that although FRP decks will never likely be able to compete on a first-cost basis with conventional construction, a life-cycle-based approach may be used to justify their use on new and rehabilitation projects.

An analysis of the LCCs of three FRP bridge systems compared with conventional reinforced concrete bridge decks is presented by Ehlen (1999). The decks in question varied in thickness from 220 mm (8.5 in.) to 340 mm (13 in.). Decks were made to span between stringers and to function as a slab bridge. The transversely spanning decks were of two types, one fabricated using a Seeman composite resin infusion molding process (SCRIMP), essentially a vacuum-based fabrication method, and the other a pultruded plank (PP) process. The slab bridge is formed using vertically oriented hollow wood cores (WCs) bonded together with resin, which separate a top and bottom shell of composite fiberglass.

The SCRIMP deck is 220 mm (8.5 in. thick) and weighs approximately one-sixth that of a traditional concrete deck. The shape is hollow with a series of inclined “webs” forming trapezoidal cells. The various deck units are placed on top of steel beams and connected to the stringers for composite action with shear pins and to each other with steel rods running perpendicular to the direction of traffic. Following deck construction, a steel railing is attached to the FRP panels, along with a polymer concrete overlay measuring 20 mm (0.75 in.) thick.

The PP deck is a pultruded glass fiber and resin system that looks very similar to hollow-core precast concrete planks used in building and some bridge construction. A series of three planks are pultruded and joined making a single, 610-mm (2-ft)-wide plank that spans transversely to the beams. This system is the same thickness as the SCRIMP decking, 220 mm (8.5 in.). Unlike the SCRIMP system, however, the PP decks are not composite with the underlying beams, lending to a somewhat larger primary bending member.

The WC deck is fabricated in much larger sections, 2.4 m (8 ft) wide and 18.3 m (60 ft) long. One edge of each deck is partially stepped so that adjacent sections overlap and can be sanded and bonded in the field. Similar to the other systems, a steel rail is attached directly to the decking and a thin polymer concrete overlay is applied.

Selection of one of these deck systems over another affects the total bridge cost. The use of hollow cores reduces the expense of material and also creates a very light deck that is easy to fabricate, transport, and install rapidly. Additionally, the lightness of the deck plays a role in reducing total structural weight and can result in savings in superstructure and substructure costs. Conversely, a deck that does not act compositely with the stringers, such as the PP deck in this example, results in a more costly stringer because of the loss of composite action and reduced load distribution. However, such a deck requires no special pockets for shear connectors.

To assess the LCC of the various systems and to judge the sensitivity of the analysis to variations in unit costs, a mathematical scenario was created to evaluate the various deck options: a CIP conventional deck versus the three FRP systems. Costs related those to the construction, maintenance, and disposal of a deck that had been in service for 40 years in North Carolina were considered. The scenario proposed that a bridge deck measuring 16.8 m (55 ft) wide, with two end spans of 9.8 m (32 ft) and a center span of 26 m (86 ft), would need to be constructed using seven precast concrete beams. The bridge was assumed to carry two lanes of a secondary road over an Interstate, has a present year ADT of 30,000 vpd, a future year ADT of 50,000 vpd, and shall be designed for MS 18 (HS 20) loading with an L/800 deflection limit. The most cost-effective deck is the one with the lowest total LCC.

Agency and user costs were considered. The agency costs were varied to include or disregard the "new material costs" that typically are true project costs when beginning construction with a new material. These costs, however, decrease with time and experience. User costs included driver delay costs, vehicle operating costs, and costs owing to increased vehicle accidents. Values were assigned to each of these items as part of the assessment and were obtained from the North Carolina and California DOTs.

The analysis indicated that the WC deck had the lowest LCC, followed by the CIP deck, the SCRIMP deck, and finally the PP deck, with the costs being $891,000, $985,000, $1.11 million, and $1.36 million, respectively. The WC deck had a higher agency cost over its life span than the CIP deck by approximately $80,000, but lower user costs, thus leading to a lower total LCC. Disregarding the new material costs, the agency expense for the CIP and WC decks is essentially the same; however, both are one-half (or less) the price of the SCRIMP or PP systems.

A sensitivity analysis of the systems costs that considers uncertainties in first and maintenance costs for the FRP deck systems was conducted to determine the initial set of conditions that would bound the costs. The costs for the conventional deck were modeled as a "best guess" ±10%, whereas for the FRP decks the range was expanded to 25%. A Monte Carlo simulation of 1,000 samples was conducted. From the simulation, probabilities of costs were computed for the various systems. The results indicated that even for a number of simulations the costs of the CIP and WC decks were essentially the same. The costs of the SCRIMP and PP decks were also similar, but on the order of twice the cost of the CIP and WC systems. Although the WC and CIP systems appear to be equal as cost-effective alternatives based on LCC methods, the LCC of the FRP systems is heavily dependent on substantial user costs during construction. If these costs are not realized, as in low-volume road applications, the LCC model would indicate no cost-effective alternative to conventional decks. Ehlen states "In locations with little traffic, none of the three alternatives had sufficient user costs savings to overcome the relatively large initial costs of their construction."

FRP Slab Bridges The replacement of a severely deteriorated rural two-lane highway bridge in Steuben County, New York, is described in Alampalli et al. (2000). The existing concrete slab bridge is a somewhat typical rural bridge with an ADT of 300 vpd with 17% trucks. The approaches consist of two lanes, 2.75 m (9 ft) wide having 900 mm (3 ft) shoulders. The out-to-out bridge width is 10 m (30.5 ft). The total bridge length is 7.6 m (25 ft) with a clear span of 6.4 m (21 ft). On the New York State condition rating scale, the bridge was rated as only marginally better than "totally deteriorated" and had a sufficiency rating of 40. In 1997, the bridge was posted for 89 kN (10 tons) and it was noted that a permanent solution could not be programmed and constructed until January 2000. Located in an agricultural area, the loss of the bridge for a long time would cause significant problems for the local economy and business and farm owners.

Because the NYSDOT was already considering the concept of constructing an FRP bridge, it was decided to use the Steuben County structure as a demonstration project. By maintaining the existing roadway geometry (horizontal and vertical) and not changing the waterway opening (other than the additional freeboard provided by a new, shallower FRP structure), the project was completed in less time than a conventional replacement with an estimated savings of $477,000 in roadway approach work.

Following partial reconstruction of the abutments owing to extensive deterioration, the new bridge was installed in halves. Each section measured 5.0 m (16.5 ft) wide, 7.8 m (25.6 ft) long, and 620 mm (24.4 in.) thick, with a 10-mm (0.4-in.)-thick polymer concrete integral wearing surface. The FRP deck panels have a closed-cell foam core measuring 600 mm (24 in.) tall separating the upper and lower mats. A keyway and an epoxy joint are used to join the two halves. The new structure was designed to AASHTO MS 22.5 (HS 25) loading, an L/800 defection limit, and an FRP strain limit of 20% of ultimate. Because of deflections limiting the design, the anticipated ratings were MS 120 (HS 118) at the inventory level and MS 160 (HS 158) at the operating level. Results from the load test indicated that the actual ratings were even higher. Reinforcement was cast into the fascia edge of each deck panel to allow for the construction of a concrete railing.

Both sections [each weighing approximately 71 kN (16 kips)] were hauled to the site on a single truck. A rented crane was used to erect the panels in approximately 6 h. NYSDOT Region 6 employees built the bridge and the approach. The bridge was opened to traffic in October 1998, approximately 5.5 months after the old bridge was demolished and significantly ahead of the projected January 2000 date estimated for a conventional superstructure replacement.

A small delamination in the bottom of the FRP was detected approximately 1.5 years after completion and was repaired by resin injection. Additionally, heavy wear of the concrete wearing surface (attributable to snow plows and heavy equipment used for grading operations) at the bridge ends was noted. The old surface was cleaned and a topcoat was applied.

The costs for the project, excluding manufacturer's profit and in-house engineering, were reported to be approximately $400,000. Had the project been funded through the NYSDOT capital program, with the corresponding hydraulic and geometric requirements, the estimated project cost would have been $1,459,000, in addition to a longer construction time. By using local work crews and an innovative material, a significantly deteriorated bridge was replaced in a short time and in a cost-effective manner.

The fabrication, testing, and installation of an all-FRP bridge over No-Name Creek in Russell County, Kansas, is described in detail by Plunkett (1997). This single-span bridge spans 7.1 m (23.25 ft) and has an out-to-out width of 8.45 m (27.75 ft). The design criteria included AASHTO MS 22.5 (HS 25) loading plus 30% impact with a target allowable live load plus impact deflection of L/800. The bridge rests on abutments consisting of steel sheet piles with a transverse steel ledge beam to support the FRP panels. An all-FRP railing system is also used, connected directly to the panels. The aforementioned structure, consisting of three longitudinal panels joined together in the field, and including railings and overlay, was installed in one and a half days.

The panels are honeycomb construction. Honeycomb voids were used to space the multilayered glass fiber top and bottom sandwich layers. The spacers also carry the horizontal shear stresses between the face layers. The total panel thickness is 572 mm (22.5 in.), with a 19-mm (0.75-in.)-thick lower surface and a 12.7-mm (0.5-in.)-thick upper surface. Because of the depth of the system and the inherent lightness of the FRP materials, each panel, approximately one-third of the bridge, weighs an average of 3650 kg (8,050 lb), which includes the 19 mm (0.75 in.) shop-applied polymer concrete overlay. The panel density, again including the overlay, is only 185 kg/m^2 (37.8 psf). This light superstructure can be easily installed with small equipment and allows for the continued use of existing substructures in most cases as weight of the replacement structure is significantly less than that removed.

One of the intended applications for the system was to have standard prefabricated modules available with incremental lengths of 0.6 m (2 ft) for purposes of rapid replacement of deteriorated or damaged bridges. For existing span lengths that do not perfectly match the stocked lengths, modifications to the backwall and approaches are required to accommodate the next longer length of panel.

Following the two-day installation procedure, the bridge was load tested to determine the in-place response of the structure. Two dump trucks were used in the field test, each with its rear axle positioned at midspan. With a combined axle load from both trucks of 376 kN (84.5 kips) at midspan, a deflection of 4.6 mm (0.18 in.) occurred for a ratio of L/1450, 56% stiffer than expected. Over the next few months additional tests were completed; other than thermal differences, no other changes in behavior were detected. The initial cost of this project was noted to be 10% to 15% higher than a conventional structure; however, the ease of construction and reduced installation time were not included.

FRP Bridge Decks FRP bridge decks may be used to rehabilitate older bridges requiring deck replacements and/or increases in load capacity as well as in new structures.

Kansas Structural Composites, Inc. (KSCI 2001) reported on two small bridge deck replacement projects. Both bridges, located on State Highway 126 in Crawford County, measured 13.7 m (45 ft) long and 9.75 m (32 ft) wide, and had deteriorated decks requiring widening. The new decks and the rehabilitated bridge were designed for an MS 22.5 (HS 25) live load. Because of the difference in thickness between the removed concrete deck and the replacement panels, a series of saddles was fabricated for the haunches between the steel stringers and FRP decks. The replacement decks were then bolted to the saddles and stringers for ease of removal in case the bridge required additional widening.

Another of the pre-engineered FRP deck systems used for spanning between an underlying support system has a triangular cell system weighing 19 psf. This deck system can be used to reduce self-weight and to effectively increase the live-load capacity of deficient structures (Martin Marietta Composites 2001).

To date, the deck system has been used successfully on various support systems including steel, concrete, and all-composite beams. The decks can be made to act compositely with the stringers and are able to support steel or concrete barrier rails. Examples of bridge projects where the system has been used include the rehabilitation of the Schroon River Truss Bridge in Warrensburg New York; a truss bridge with steel stringers in Harford County, Maryland; and in the Lewis & Clark Bascule lift bridge in Astoria, Oregon.

In a significantly more involved project, an old steel-stringer bridge with a timber deck was replaced with FRP-pultruded wide-flange shapes and an FRP deck ("Light but Strong" 1997). Known as the Laurel Lick bridge replacement, this project used a system of pultruded FRP decks, which are also described in *Superdeck Product Brochure* (2001). In addition to the all-FRP superstructure, the substructure constructed was mostly FRP as well. For the abutments, FRP piles were placed in holes drilled in limestone and grouted. FRP lagging was placed between the piles to form a pile-and-lagging abutment with a poured-in-place concrete cap. The new bridge is 6.1 m (20 ft) long and 4.9 m (16 ft) wide, and the deck is 200 mm (8 in.) thick. The FRP stringers are 305 mm (12 in.) deep and 305 mm (12 in.) wide, with a 12.7 mm (0.5 in.) constant web and flange thickness. The deck is adhesively bonded to the stringers and additionally fastened with the use of blind "Huck Bolts"; a polymer concrete overlay was provided.

Construction of the new bridge required only 23 working days including the foundation. A crew of four with light equipment constructed the entire bridge, with many of the items being placed by hand or with the aid of a small capacity excavator as the "crane" for the job.

In addition to the Laurel Lick all-FRP project, the use of the system of pultruded FRP decks on a series of bridge rehabilitation projects is described in the *Superdeck Product Brochure* (2001). The system is a pultruded glass-fiber honeycomb deck system composed of various deck sections and shear keys to connect the deck elements that are epoxied together in the field. Designed to support MS 22.5 (HS 25) vehicular loads and available in various span lengths (which are a function of live-load deflection criteria), the decks are used to replace deteriorated bridge decks. Examples of these installations include

- Laurel Run Road, Somerset County, Pennsylvania—8.66 m (22 ft) span, 10.04 m (25.5 ft) wide bridge, FRP deck on galvanized steel stringers.
- Wickwire Run, Taylor County, West Virginia—9.14 m (30 ft) span, 6.6 m (21.7 ft) wide bridge, FRP deck composite with galvanized steel stringers.

Other FRP Product Applications The testing, design, and construction of a bowstring through-truss bridge made of fiber-reinforced plastic lumber (FRPL) are discussed in McLaren et al. (2001). FRPL is a lumber substitute composed of recycled plastics (essentially recycled plastic milk jugs), which has strength similar to traditional wood products, although it has less stiffness. The project described is a stream crossing in New York State. The single-lane bridge has a 3.35-m (11-ft)-wide roadway and a 9.1 m (30 ft) span, and it was designed for an AASHTO MS 13.5 (HS 15) live load.

The design of the bridge considered the newness of the proposed material and was based on an allowable stress design philosophy, with the allowable stresses being corrected for temperature and load duration owing to the creep potential of the FRPL. The top chord is composed of five FRPL 50 x 200 mm (2 x 8 in.) members laminated together along their wide faces to form the curved top chord. The bottom chord is made of 200 x 200 mm (8 x 8 in.) FRPL "timbers." The verticals are also FRPL, whereas steel rods were used for the diagonals, because it was anticipated that the FRPL diagonals would be difficult to frame and erect. Because of the flexibility of the FRPL members, the floor beams were flitched beams with a steel plate sandwiched between two FRPL members to increase stiffness and load-carrying capacity. The total weight of the FRPL used in the bridge was 5000 kg (11,000 lb), plus 2450 kg (5,400 lb) of steel in the connection plates, flitch beams, and tie rods. The bridge was load tested on completion and will be monitored and tested over a 5-year period to obtain additional data on the behavior of this novel structure.

Recognizing the need to develop local system bridge replacements that are durable, lightweight, and easy to install, the commonwealth of Virginia is exploring the use of FRP stringers in the reconstruction of deficient short-span bridges (Hayes 2001). The technology used is a double-web box beam stringer made from pultruded or vacuum-assisted molding. The webs are fiberglass and vinyl resins, and carbon fiber is used in the flanges to create a hybrid beam of much higher stiffness than an all-glass counterpart.

The proposed implementation was for the reconstruction of Route 601 over Dickey Creek in Virginia. The existing bridge (built in 1932 and classified as in poor condition) has steel stringers, rubble abutments, and timber deck and rails. The replacement structure [designed using the AASHTO specifications for a live load of MS 18 (HS 20)] will be 4.6 m (15 ft) wide and have a span of 11.9 m (39 ft). A timber deck and asphalt overlay will be used with the FRP beams. The structure was designed as a multi-stringer bridge and for the deflection criteria of L/800. The required girder spacing was 1.1 m (3.5 ft). The bridge was designed to be noncomposite because of difficulties in obtaining composite action between the glulam bridge deck and the FRP stringers. The diaphragms at midspan and at the abutments are made of steel and are connected with threaded steel rods through holes in the box beams. A crash-tested timber rail was used for this bridge.

Bridge Elimination for Low Water Stream Crossings

As previously noted, the focus of this chapter is to find new and innovative ways of constructing low-cost and low-maintenance short-span bridges to replace aging and deteriorating structures. However, the new bridge will still have an initial expense and associated maintenance costs. An alternative concept is to replace a short-span bridge over a low-flow stream with an embankment; in essence, replacing the bridge with roadway. This concept, which is discussed in detail in *Low Water Stream Crossings: Design and Construction Recommendations* (Lohnes et al. 2001) should only be considered if flood occurrence levels are tolerable. For small streams, especially ephemeral streams with intermittent or low persistent flow, closure of the crossing may be a financially expedient decision. This solution also eliminates the liability risk associated with the continued use of a deficient bridge.

The concept of low-water stream crossing replacement centers around the idea that streams (or drainage ditches) with very low persistent flows, or ones that are dry except for occasional flood conveyance, may be effectively closed by filling in the old bridge opening with roadway embankment. Lohnes et al. (2001) discussed three options for low-water stream crossings: unvented ford, vented ford, and low-water bridges. A brief description of these options follows.

The unvented ford is essentially a dammed stream. Its application is appropriate where the normal stream depth is less than 150 mm (6 in.) and where the proposed roadway crossing is less than 1.2 m (4 ft) above the level of the streambed. The embankment may be constructed of crushed stone, riprap, precast concrete slabs, or other suitable materials. The vented ford is a variation on the previous concept, but is used for somewhat higher flows. In the vented ford, several vent pipes are placed in the embankment. For low-flow conditions, the pipes remain above the normal stream elevation. For moderately higher flows the pipes convey a portion of the floodwaters; in high-flow situations, the road will be temporarily overtopped. The last option is the low-water bridge crossing. These bridges may be flat slabs or several other low profile options described in Lohnes et al. (2001). The bridge structure allows for the greatest conveyance before overtopping but the roadway profile is still kept at a minimal freeboard over the stream and will be overtopped during some flood events.

The considerations for choosing the appropriate crossing type include

- Type of stream (perennial, intermittent, ephemeral),
- Type of road (paved, gravel, dirt),
- Use of road,
- Channel geometry,
- Manning's coefficient,
- Roadway geometry,
- Drainage area,
- Wetlands,
- Historic daily discharges, and
- Anticipated duration of road closure.

A series of discharge curves for several hydrologic regions in Iowa are presented, and similar curves could be developed for other hydrologically distinct areas. The user selects the design discharge as a function of drainage area and selected probability of exceedence.

The recommended site conditions for implementing low-water stream crossings include roads that are generally unpaved (gravel or dirt), field-access roads, roads with no inhabited dwellings, low-volume roads, and roads with available detours. These criteria may be tailored by individual agencies. Additionally, the stream should have a stable channel, roadway approach grades shall be less than 10%, the height between the proposed roadway and the streambed should be less than 3.65 m (12 ft), costs should be compared with a bridge, and the site should not be in an area where future development might require construction of a bridge. Following determination of the suitability of the site in general, Lohnes et al. (2001) presented design procedures for the three crossing types.

Also included in this report are recommendations for appropriate traffic signing in the vicinity of the potentially flooded "bridge" and a discussion of legal concerns about this type of construction. Of the 225 low-water stream crossings in Iowa, some in service for more than 20 years, only three legal claims have been filed. In two cases involving crashes, the counties were absolved, and in the third case the issue concerned a right-of-way issue and not the crossing itself. It is advised, however, that a stated design criterion be established as a minimal protection against tort liability.

In a survey conducted in conjunction with the project, Lohnes et al. gathered local agency input regarding various aspects of low-water stream crossings. Design typically considers drainage area and stream gradient, is done with in-house design standards, and is constructed almost exclusively with local agency forces. It was learned that the preferred option is the vented ford, with approximately 40% of respondents indicating this as their first preference. Agencies having experience with low-water stream crossings provided meaningful suggestions for improving their performance. Low-water stream crossings should not be constructed with small diameter pipes, in deep channels, at skewed crossings, on erodible soils, and on dead-end roads. Appropriate locations include those with well-defined channels, when constructed without pipes on low roads near rivers prone to flooding, and on low-volume roads. Roadway slopes should be gradual, a rational design storm should be used (i.e., a 5-year storm), side slopes should be protected, and appropriate signage should be used. More than 70% of the agencies responding to the questionnaire indicated that if a design manual existed (such as the one eventually developed by Lohnes et al. and described herein), they would consider low-water stream crossings. One might infer that similarly affirmative responses would come from other agencies in other states if presented with the same concepts. In general, low-water stream crossings appear to be viable solutions in certain situations.

OFF-SYSTEM BRIDGE DESIGN AIDS AND EXPEDIENTS

Survey question (BT-5) was included to obtain information on the use of engineering software or other types of design aids, which is closely related to the pre-engineered products. It was of interest to determine how bridges were being designed on off-system roadways and what resources the local agencies have available to expedite the engineering design process. Any tools that can shorten the design process save funds, which can then be used for bridge maintenance, rehabilitation, new construction, etc.

Various design aids are available and were cited in the survey responses. In general, the responses indicated the use of state standards as design guides, plus several available from other sources. The other sources included standard plans for timber structures available from the USDA FLP, the standard plans and software for short-span steel bridge design developed by the American Iron and Steel Institute (AISI), and the design manuals for precast concrete frame structures. The lack of use (or citation of use) of the many other design aids most likely is an indication that they are an underused resource.

A number of software programs exist and were cited, both those that are commercially available and those developed by state agencies. A listing of cited software is presented in Appendix A in the response to survey question BT-5. A number of respondents referenced the PennDOT software programs. It is of interest to the potential users of this synthesis that PennDOT makes their numerous engineering design programs available to other government agencies at no cost. There are a wide array of programs covering various bridge superstructures, substructures, and bridge rating functions.

Standard Plans

The use of standard plans has the potential for reducing the total cost of bridge replacements by minimizing engineering effort, which in turn reduces the associated administrative and overhead costs. Equally as important, if not more so, is the standardized construction of various components and details whose performance has been tested over time. The combination of minimization of engineering and familiarity during construction has the effect of leveraging funds for construction. A number of concepts for standardization are described herein. They vary in their actual presentation from pre-engineered complete systems to more generic design aids.

FHWA Standard Plans

In the past, one of the design tools used by both state and local agencies was the FHWA's *Standard Plans for Highway Bridges* (FHWA 1976, 1979, 1982, 1984). Published in several volumes and including designs and details for various bridge types, including concrete, steel, and timber simple-span bridges, as well as load factor designs for continuous concrete slabs, prestressed concrete I-beams, steel rolled shapes, and steel plate girders, the plans were intended to be used as a guide in the development of local standards. Although no longer published by the FHWA owing to the proliferation of state standards and the difficulty in keeping the plans updated for code changes, these plans are likely still available at various DOTs and consulting firms and can still be of value in the construction of off-system bridges. The preface to the plan sets states the following:

> These plans are intended to serve as a useful guide to state, county, and local highway departments in the development of suitable and economical bridge designs for primary, secondary, and urban highways. The plans should be particularly valuable to the smaller highway departments with limited engineering staffs.

With this description, it appears clear that the plans may be of some use in the design and construction of off-system bridges, in particular by local agencies that may lack the standards and staff to fully engineer and detail replacement bridges.

Definite engineering issues need to be addressed with some of the plans because of changes in design specifications through the years, and there are also details presented that are no longer used owing to their obsolescence or cost-inefficiency. However, for some of the bridges depicted in the plan sets, the overall general design does not vary significantly from a modern design. In that context, the plans can be used to evaluate the feasibility of various bridge options for given span arrangements and bridge widths, can be used to determine relative costs between bridge types, and can also be used as a preliminary design to be refined and updated to modern design standards. Users of the FHWA plans should use them as no more than a guide and preliminary engineering tool because of their obsolescence, and should consult with various material suppliers and fabricators regarding regional factors that might affect the selected bridge type. Consultation with the state agency may also reveal the existence of bridge standards very similar to the FHWA plans, but updated to current codes and the agency's preferences. Also, various industries such as the steel, timber, and concrete bridge trade associations [AISI, American Institute of Timber Construction (AITC), USDA FPL, Concrete Reinforcing Steel Institute (CRSI), Portland Cement Association, Precast/Prestressed Concrete Institute, etc.] have published their own plan sets in recent years in the same spirit as the FHWA plans, but with updated details and modern design criteria. These design aids are discussed in this synthesis as well.

Because it was the intent of the FHWA plans to spur the development of local agency standards, the process of doing so by several highway agencies is discussed in the following sections.

Iowa DOT County Road Bridge Standards

The Iowa DOT maintains an extensive set of bridge design standards that can easily expedite the creation of bridge plans. These plans include pre-engineered prestressed I-beam bridges, standard drawings for integral and stub abutments, predesigned continuous concrete slab bridges, barrier rails, and many predrawn transverse and longitudinal sections for various roadway geometries. The assembly of a completed plan set is a fairly easy process, with the exception of the design of piers, abutment piles, and quantity determination. To further expedite and standardize the design and construction of bridges on the county road system, the Iowa DOT also maintains a complete set of pre-engineered county bridge standards. These standard plans encompass a complete set of construction drawings for continuous concrete slab and prestressed I-beam structures, including various options for pier and abutment construction. Pre-engineered pile bent designs are also provided. A brief description of the various county bridge standards is presented in the following paragraphs.

The Iowa DOT J24 standard provides complete engineering plans, including tabulated bridge quantities, for a series of continuous concrete slab bridges with 7.3 m (24 ft) roadway widths. The predesigned and detailed structures are all three-span construction, with the total bridge lengths ranging from 23 to 38 m (75 to 125 ft) in 3.8 m (12.5 ft) increments. The bridges generally have the proportions of 0.8L–L–0.8L. In addition to the five tabulated bridge lengths, the designs are also presented in four skew angles, 0, 15, 30, and 45 degrees, use integral abutments on a single row of timber or steel piles, have two types of pier caps (monolithic and nonmonolithic) with open pile bent pier structures, and employ two railing types, a typical Jersey-type railing and an open concrete railing.

To use the J24 standards, the bridge length and skew that most closely approximates the span to be constructed is chosen and the plans either modified to fit the minor deviations at the site or the site is changed to fit the bridge. Complete quantities and details are presented for bidding and construction purposes and the designs are maintained and approved by the state DOT for use on the county road system. Standardization of the designs and use of these standard drawings likely improves the quality of the constructed project and reduces costs because of the familiarity of all parties with the bridge concepts.

The J30 series is an extension of the J24 standards. The J30 plans encompass the same span length, skew, abutment, and pier types as the J24 series, but are intended to be used for bridges with a slightly wider roadway width, 9.1 m (30 ft).

A similar set of plans is provided for prestressed I-beam bridges. Denoted H24, H24S, H30, and H30S, these four sets of plans provide complete designs, including piers and abutments, for 7.3-m (24-ft)-wide roadway bridges in three-span or single-span construction (H24 and H24S) and the same types of details for a 9.1-m (30-ft)-roadway width (H30 and H30S). For the simple span series of plans, the spans vary from 9.1 to 24.4 m (30 to 80 ft). The three-span continuous designs have total bridge lengths ranging from 38 to 74 m (126 to 243 ft).

For the simple span bridge plans, the predesigned abutment is a combination timber and concrete structure. A single row of timber friction soldier piles is depicted extending up to just below the beam seat elevation. A concrete pile cap is poured to support the concrete I-beams. Timber lagging is placed between the driven piles to retain the fill. The timber wingwalls that are used are tied together with tie rods, and the abutment soldier piles are tied back to a deadman.

For the continuous bridges integral abutments are depicted. For shorter spans, timber piles may be used, whereas for the longer three-span bridge designs steel piles are required because of their vertical load capacity and their greater ability to accommodate the required lateral movements. Several pier types are presented, including open pile bent piers with concrete caps using concrete-filled steel pipe piles, prestressed concrete piles, or concrete-encased steel H-piles. The required bearing is listed for the various bridge designs. Solid stem hammerhead piers are presented for use where debris accumulation or ice loading is a design consideration. These piers are designed for a predetermined ice load. Various footing designs are illustrated for these piers using steel piles, timber piles, or spread footings keyed into rock.

PennDOT Standard Plans for Low-Cost Bridges (BLC Series)

Through the years PennDOT has maintained a series of design aids intended to expedite the design process and result in standardized, economical designs for ordinary bridge structures. The PennDOT BLC series of plans is *not* a collection of predesigned bridges in the sense that a series of plans are available in various predetermined sizes; rather, the plans have much more flexibility and are a complete superstructure and substructure design set. Although many of these standard plans are no longer updated or have been discontinued in favor of their automated engineering and drafting program, BRADD, the department continues to support the standard plans for timber structures. A description of several of the standard plan sets is presented herein, again recognizing however that some of the plans are no longer supported by the department or have been superceded.

Timber Bridge BLCs An aid for the design and construction of hardwood glulam bridges has been prepared by PennDOT for use at stream crossings on the secondary road system (*Standards for Hardwood Glulam* . . . 1998). These SI unit plans are available in printed form or by download from the PennDOT website. A U.S. customary version, BLC-560, is also available.

The PennDOT BLC-560M series of plans is divided into several components, design sheets, and construction sheets. The design sheets include an example illustrating application of the BLC principles as well as data assembly sheets. The data assembly sheets assist the engineer in determining the various dimensions, quantities, member sizes, etc., for the design and plan preparation for glulam beams, glulam longitudinal panels, steel beams supporting timber decks, spread footing abutments, pile-supported abutments, and pile-supported timber sills. The BLC construction sheets are predrawn plans for construction with project-specific information left blank with placeholders. Much of the information for these sheets comes from either survey information, project design constraints (span size, bridge width, skew, etc.), or from information computed with the assistance of the various data assembly sheets. The timber bridge BLCs cover the design of bridges from 5.5 to 30.0 m (18 to 98 ft) in length. Roadway widths can vary from 7.2 to 9.6 m (24 to 36 ft) and the skew angle from a nonskewed bridge to 45 degrees. The traffic loading is the AASHTO LRFD HL 93 loading as modified by PennDOT with traffic restrictions of 750 vpd and fewer than 25 trucks per day.

To prepare a complete set of construction plans, the designer starts with the various data assembly sheets, selecting the appropriate sheets for the type of superstructure and substructure to be constructed. Once the data assembly sheets are completed, the results are transferred to the construction sheets. There is little engineering required in this process; rather, it is more a matter of bookkeeping to ensure that the proper terms are computed and transferred to the appropriate locations.

Steel and Concrete Bridge BLCs Although no longer supported or updated by PennDOT, a series of standards has been published comprising various bridge designs using steel or concrete superstructures for short-to-medium-span bridges. These standards provide a wide variety of selections concerning beam type, span length, available skew angles, substructure choices, etc. Unlike the timber bridge plans, which are in accordance with the AASHTO LRFD design code as modified by PennDOT, the steel and concrete plans discussed in the following paragraphs are of an older vintage and generally in accordance with the AASHTO *Standard Specifications* (in effect at the time the plans were published) with a live load of MS 22.5 (HS 25), along with a state-specified 900 kN (204 kip) permit load vehicle.

For very short structures, PennDOT produced the *Standard Plans for Low Cost Bridges, Series BLC-520 Spans 18'–35'* (1983b). A large number of off-system bridges could be designed with this plan set owing to the short span length of a large number of existing deficient bridges. The types of bridges contained in the BLC-520 plans include prestressed concrete adjacent box beams, reinforced concrete precast channel beams, and rolled shape steel beams. Three types of abutments are also included: traditional concrete abutments on spread footings with cheek walls and flared wingwalls, a straight stub abutment on spread footings with the wings simply being a parallel extension to the abutment stem, and a variant of the straight wing abutment on piles. These plans can be used to design and detail bridges with roadway widths varying from 6.7 to 14.6 m (22 to 48 ft), providing a great deal of flexibility for various classes of bridges and roadways. Similar to the timber bridge BLC plans, various data assembly sheets are employed to obtain the appropriate beam sizes, slab reinforcing, abutment dimensions, quantities, etc. Following calculation of these various dimensions, elevations, quantities, etc., they are transferred to the construction sheets to complete the project deliverable.

For bridges in the intermediate span range, PennDOT developed *Standard Plans for Low Cost Bridges Series BLC-510 Spans 35'–90'* as an extension of the short span plans (1983a). Because of the longer spans depicted in this BLC series, the beam and bridge types vary somewhat from those for the very short spans previously described. The superstructure types now include adjacent or spread prestressed concrete box beam designs in various depths, a series of noncomposite and composite rolled shape beam designs, and designs for abutments with spread footing or pile-supported footings. Various deck widths are provided.

Finally, *Standard Plans for Low Cost Bridges Series BLC-500 Span 90'–130'* (1983c) are intended to replace what could be considered the longest simple spans for which standard designs are a reasonable solution. With only a slight variation in the roadway widths, these plans provide tailored solutions for bridges composed of pre-engineered steel plate girders, simple span prestressed concrete I-beams with straight strand patterns and selective debonding for stress control, and adjacent concrete box beams with debonding used again for crack control. Two types of abutments are presented, stub abutments on piles and high abutments on piles with only minimal cover over the footing.

Culvert BLCs PennDOT has also developed and maintained a series of low-cost standards for culverts, *Standard Plans for Low Cost Bridges Series BLC-530 Buried Structures* (1985). These plans function in the same manner as the bridge plans. Once a structure type is selected, the designer compiles the various data assembly sheets necessary to complete the construction plans and computes or determines the various pieces of information to be transferred to the construction drawings. A number of buried structures are depicted in the aforementioned plan set, including a metal plate pipe arch with toewall, metal plate pipe arch with headwall, metal plate arch/box with headwall, reinforced concrete rigid frame with headwall, precast reinforced concrete box with headwall, and CIP reinforced concrete box with headwall. In addition to the structure type, gabion endwalls and wingwalls are depicted, as are design and details for conventional reinforced concrete wingwalls. Limitations on fill height are given for the various structures and some of the options can be used in multicell configurations for longer spans or increased hydraulic flows.

Texas DOT Off-System Bridge Standards

The Texas DOT (TxDOT), like the other state agencies mentioned, has a series of bridge standard plan sheets, some of which are especially appropriate for off-system bridges. A brief discussion of these standards follows. The plan sheets are based on a standard off-system roadway width of 7.3 m (24 ft) and have various bridge options.

The TxDOT presents several variations of prestressed concrete I-beam designs. For short-to-medium spans, three AASHTO-type I-beams, denoted Types A–C, are used. For a standard cross section with beams spaced 2.0 m (6.67 ft) centers, depending on the beam type used, simple span beam designs are presented for spans ranging from 9 to 26 m (30 to 85 ft). The required concrete strength and prestressing strand pattern are shown. For the Type C beams, the deepest section, wider beam spacings are also available as a result of the efficiency of the section. Slab reinforcing plans, transverse sections, and miscellaneous details required for construction are presented. Various pre-engineered and detailed abutments are also provided for the prestressed I-beam bridges. The plans include skew options of 0, 15, and 30 degrees. Similar to the preengineered and detailed abutments are a series of pre-designed intermediate bents. The typical bent has two concrete circular columns for which all quantities are tabulated. Pile or drilled shaft loads for several footing configurations are given.

In addition to the precast concrete I-beams, requiring traditional slab forming, are precast and prestressed concrete double-T beams, with either a composite concrete topping placed after unit erection or a noncomposite asphalt topping placed on sections with slightly thicker flanges. For beams with concrete topping, depending on beam depth and concrete strength, beam spans ranging from 9 to 15 m (30 to 50 ft) are provided. For the asphalt-topped beams, the span ranges are basically the same, with a maximum span limitation of 13.7 m (45 ft). As with the I-beam standards, abutment and bent details are provided in several variations. In addition to traditional circular column piers, pile bent piers are provided for the shorter spans.

Another option presented in the TxDOT standards is a CIP concrete girder bridge. Reusable metals forms (typically referred to as pan forms) are used to construct this type of bridge. The resulting bridge is composed of a series of parallel beams with the underneath appearance of a barrel vault structure. Two standard span lengths are available, 9.2 and 12.2 m (30 and 40 ft). The standard depth is approximately 0.6 m (2 ft) for the shorter span and 0.8 m (2 ft 9 in.) for the longer span.

AISI Standard Plans

In response to a need for greater standardization of steel bridge design, AISI developed a series of standard plans for simply supported steel bridges (*Short Span Steel Bridges* . . . 1998), with the intent to both standardize steel bridge design, as variance in details has long been considered a source of price inflation in steel bridge designs, and to promote steel structures as viable choices for short-to-medium-span bridges.

The plans are organized in several sections, generally by roadway widths of 7.3, 8.5, 10.4, 12.2, and 13.4 m (24, 28, 34, 40, and 44 ft) and for total span lengths ranging from 6.1 to 36.6 m (20 to 120 ft). Depending on the number of beams and the span length, various beam options are provided, including noncomposite and composite rolled beams without cover plates, composite rolled beams with welded or end-bolted cover plates, and composite plate girders with unstiffened or partially stiffened webs. The combination of beam spacing, span lengths, concrete deck types (normal or lightweight concrete), and beam types results in more than 1,100 standard designs in the plan set. In addition to the design of stringers, the slab reinforcing is detailed, as are shear stud size and spacing when required, stiffener and diaphragm connection plate sizes, cross frames or rolled shape diaphragms, pre-engineered elastomeric bearings, and schematic details for jointless and integral substructures.

Several points are made regarding the selection of appropriate beam types. The criteria of selecting steel structures based on least weight is now considered flawed, because the least-weight options frequently require the use of plate girders with varying flange sizes and the use of intermediate shear stiffeners. Comparing the material costs with labor costs, these fabrication expenses may frequently exceed any savings in materials. It is suggested that simpler detailing with heavier beams may be the more economical solution. Regional economics are obviously an important consideration and the expertise of local fabricators and contractors should be employed to help select the best options for a particular installation. A decision tree is presented to aid in the selection from the various options relative to deck type, composite versus noncomposite design, rolled shape versus plate girder, etc. The use of uncoated weathering steel is promoted as leading to both first cost and LCC savings when its use is in accordance with the restrictions presented in the FHWA Technical Advisory T5140.22, *Uncoated Weathering Steel in Structures*.

Timber Bridge Standard Plans

The WIT, a jointly funded cooperative research, development, and technology transfer program supported and funded, in part, by the FHWA and USDA FLP, has developed numerous design aids and standard plans for the implementation of modern timber bridges. These plans are described here.

One of the first sets of standard plans developed were the *Standard Plans for Southern Pine Bridges* (Lee et al. 1995). These plans were developed as a cooperative effort of the FLP, the University of Alabama, and the Southern Pine Council. Standard designs are presented for three bridge types: stress-laminated sawn-lumber slab bridges, stress-laminated glulam timber bridges, and sawn-lumber stinger bridges with transverse sawn-lumber plank decks. Designs are presented for AASHTO standard loadings, MS 18 and MS 22.5 (HS 20 and HS 25).

For the stress-laminated sawn-timber bridges, various design widths and lengths are presented, as are the number and required stressing in the transverse post-tensioning bars. Bridge widths vary from 3.6 to 11.6 m (12 to 38 ft) and spans from 3 to 6 m (10 to 20 ft). Bridges are constructed of standard southern pine, with nominal sizes ranging from 50 x 200 to 50 x 300 mm (2 x 8 to 2 x 12 in.). Quantity tables are presented for all standard bridge lengths. For quantities that are independent of bridge width, hard quantities are given, whereas for those that are dependent on deck width, formulas are provided for computing the required quantities. Because of the newness of stress-laminated sawn-timber bridges in the United States at the time of the publication of these plans, a design process and example accompanies the standard plans, which illustrates the application of the AASHTO design process, computation of governing forces, and stresses and determination of the appropriate amount of transverse prestressing.

In terms of span length, the stress-laminated glulam southern pine spans pick up where the sawn-lumber spans leave off. The stress-laminated glulam spans range in length from 6 to 9.7 m (20 to 32 ft) and are available in the same deck widths. The panels are composed of a standard 24F-V3 southern pine combination, with the deck thickness selected in accordance with the restrictions imposed by the span length. Construction guidelines are presented for creating panels from the individual laminations in place or for creation of the entire bridge panel adjacent to the bridge site, after which the completed unit can be lifted into place. Similar to the sawn-lumber-laminated bridge, design criteria and calculations are provided as backup for the standard plans and as a teaching aid for those unfamiliar with glulam stress-laminated timber slab bridges.

The final bridge type is a series of longitudinal sawn-lumber stringers with transverse timber decking placed flatwise across the deck. An asphalt wearing surface is placed over top for protection. Various sawn stringer sizes are depicted in both No. 1 and No. 2 grades and various stringer spacings. Depending on the interaction of these variables, simple spans of up to approximately 7 m (23 ft) are possible. Again, depending on the size of the stringer, lumber grade, and the stringer spacing, the required size of the transverse decking is given.

Railing and curb options are provided for all three bridge types, as are all of the details required to fabricate a bridge. Additionally, details are provided for the attachment of each of the bridge types to an abutment or for the attachment of two spans to a common intermediate bent.

A refinement and extension of these plans is presented in the *Standard Plans for Timber Bridge Superstructures* (Wacker and Smith 2001). These plans have been developed in conjunction with several government agencies, as well as with commercial partners, to provide simplified designs of timber bridges and bridge components. Included in the plans are seven bridge superstructure types, five longitudinal deck systems, and two beam systems. The designs are prepared in accordance with the AASHTO *Standard Specifications* for design loads of MS 18 or MS 22.5 (HS 20 or HS 25).

Great latitude is presented in the *Standard Plans* so that bridges of various widths, lengths, and span configurations can be constructed using various wood species; no longer are the plans restricted only to southern pine. Design options are presented for the following bridge types: nail-laminated decks, spike-laminated decks, stress-laminated sawn-lumber decks, stress-laminated glulam decks, and longitudinal glulam decks, as well as for glulam stringers with transverse glulam decks and transverse glulam decks for steel-stringer bridges. Within these bridge types, options for deck type bridges range from 3 to 17.7 m long (10 to 58 ft), with bridge roadway widths from 3.6 to 11 m (12 to 36 ft). For the glulam timber decks on steel beams there is no stipulation of bridge length because that is a function of the stringer capacity alone.

In general, the *Standard Plans* allow for the use of any of the woods listed in the AASHTO *Standard Specifications*. For each bridge type, with the exception of the glulam stringers with glulam decks, minimum required bending properties are listed as a function of the span length and the governing deflection criteria. Any species listed in AASHTO and meeting the allowable bending stress and the minimum required modulus of elasticity provided for the design scenario can be used. For the glulam-stringer and glulam deck bridges, the designs presuppose the use of western species or southern pine and the appropriate width and depth standard combinations are listed for each of these materials. Additional details provided include the layout and force requirements for transverse stressing bars for stress-laminated construction, location and size of transverse stiffener beams for multiple panel bridges, steel or wood diaphragm layouts for glulam-stringer bridges, substructure connection details, asphalt wearing course details, and references to other Forest Service plans depicting various bridge railing options for both longitudinally and transversely laminated deck panels.

Additional Design Aids

As a supplement to the use of standard plans is a less complete but useful category of information, which is classified in this report as design aids. These design aids include handbooks illustrating the design of various bridge types and design examples prepared by various industries indicating the efficient use of their various materials in the construction of economical and durable bridge designs. In the following sections these design aids are tabulated and discussed by material type.

A complement to the survey of pre-engineered products was survey question BT-5, related to the use of engineering software or other types of design aids. Any design tool that can shorten the design of low-volume road bridges can provide savings in engineering costs.

Concrete Bridges

The CRSI has a series of design aids for use in the design and construction of off-system bridges. These design aids are available in both published form and as computer programs for bridge design.

In *A New Look at Short Span Reinforced Concrete Bridges* (1983), a series of guidelines and predesigned bridges are presented relative to the selection of appropriate CIP-reinforced concrete bridge structures intended for short-span applications. Although the economic data and some of the detailing presented in this publication are somewhat dated, the designs presented are still reasonable standards for purposes of preliminary design and potentially for final design. These designs are intended to assist the engineer in selecting the appropriate balance between span length and substructure cost and in determining reasonable costs. The parameters of the designs considered a roadway consisting of two 3.35 m (11 ft) lanes and 1.8 m (6 ft) shoulders, with concrete parapets. Additionally, details were developed for bridges having total lengths of up to 40 m (130 ft) and with individual span lengths of up to 12 m (40 ft). It is noted that the designs are based on a minimum AASHTO loading of MS 18 (HS 20), because it was found that designing for a lesser load of MS 13.5 (HS 15) resulted in material savings of less than 2% of the total bridge cost. The lesser design load is also more likely to lead to future load capacity problems.

Flat slab bridges are pre-engineered for three typical span arrangements, all having a balanced span arrangement with span lengths 0.8L–1.0L–0.8L, which are typically used to economize three-span structures. The slabs have drop panel caps at the piers and are detailed with or without haunches at the piers. Cost-estimate tables, as well as total quantities, are provided so that engineers can use their own unit costs for concrete, reinforcing, and slab formwork to determine an estimated structure cost.

Designs for three multi-stringer bridges with spans of 6, 9, and 12 m (20, 30, and 40 ft) are also presented. These simple spans can be used in a multi-span arrangement with the bridge behaving as a series of simply supported spans. These designs detail the use of rectangular concrete beams with notched top flanges that can support transverse deck panels. The design allows for either CIP construction, precasting of the reinforced concrete elements, or placement of precast concrete stay-in-place forms and casting of the deck. The flexibility allows owners and contractors to minimize erection time and maximize the use of forms by precasting the beams remotely or on site. If desired, several sets of forms can be built to minimize total construction time. Again, quantities and details are presented for the several sample designs.

For stream crossings where owing to stream width and berm lengths a two-span bridge is required, an alternate solution is suggested that uses tall wingwalls and abutments in conjunction with a shorter main span. The cost of tall wings and abutments needs to be compared with the alternative of short abutments, two spans, and a stream-located pier. Hydraulics are an important consideration when considering this possibility, because the waterway opening will be significantly reduced with the tall wings.

In addition to the standardized superstructure options presented, a series of standard substructure designs are included for use in conjunction with the pre-engineered superstructures. Bridge piers both with and without a cap beam are illustrated. For piers without a cap beam, the column reinforcing terminates within the confines of the bridge slab, which makes the columns integral with the superstructure. In addition to column spacing and column and cap detailing, sample footings on piles, along with footing size and reinforcing, are presented for the several example bridges. Options are also presented for a pile bent pier, a solid wall pier, and for an option that uses site-precast concrete columns in conjunction with the site-precast-stringer bridge system.

Steel Bridges

Other than the AISI *Standard Plans* previously discussed in this chapter, no other design aids have been located relative to expediting the design of steel bridges.

Timber Bridges

In addition to the various standard plans for timber bridges previously discussed, a number of timber design aids are available. Some of these come from timber product manufacturers and are in the form of design curves, charts, tables, etc., and some are from trade associations.

In 1999, the AITC published a guide that leads prospective timber bridge designers through the design of modern timber bridges. This guide, *Glued Laminated Timber Bridge Systems*, has additional information on various aspects of timber bridge design, fabrication, and construction.

The main thrust of the AITC manual is the design of three bridge types: longitudinal deck bridges (without transverse post-tensioning), transversely post-tensioned timber slab bridges, and glulam-stringer and deck bridges. Design examples are presented for each of the three bridges. Additionally, tabulated designs are available for design loads of MS 13.5, MS 18, and MS 22.5 (HS 15, HS 20, and HS 25) for each of these bridges.

The longitudinal deck bridge without transverse post-tensioning uses a spreader beam to tie the panels together and to assist in the load distribution that is similar to a design presented in the USDA FPL plans (Wacker and Smith 2001). Options are presented for the longitudinal decks that vary based on design live load and continuity (single span or multi-span continuous). When using the standard designs, one must make sure that the species selected, after being modified for load duration, moisture condition, etc., meets the minimum bending stress, shear stress, and modulus of elasticity specified. Once this has been done, allowable spans are tabulated versus deck thickness. For this deck type, the maximum span for the heaviest live load, MS 22.5 (HS 25) is 7.9 m (26 ft) for both simple and continuous designs. There is minimal increase in span length for lower design loads.

The longitudinal-stringer bridge with transverse deck panels is an all-timber bridge with glulam products in all elements. The tabulated standard designs are based on western species and a 24F-V4 combination (a standard glulam beam as described by the National Design Specifications); southern pine sizes might be somewhat smaller than those tabulated. Again, a species must be selected that after application of the appropriate modifiers meets the minimum allowable stresses and material properties requirements. Span lengths of up to 22 m (72 ft) are listed for MS 22.5 (HS 25) live loading. For the lowest live loading of MS 13.5 (HS 15), the maximum span listed is 24.4 m (80 ft), only 2.4 m (8 ft) longer. Again, there is minimal benefit in using the smaller design load in terms of span length; however, larger stringer sizes are required with the heavier design load.

The final option is a stress-laminated glulam deck bridge. For this bridge type, tabulated options are listed for MS 18 and MS 22.5 (HS 20 and HS 25). In both cases, the maximum span is listed as 15.2 m (50 ft), with a slightly thicker deck being required for the heavier live-load condition. The required material properties and transverse stressing requirements are the same or essentially the same for either live-load option. The designs for the stress-laminated bridge are based on southern pine; western species sizes would be slightly larger.

Other Sources of Design Information

A number of additional resources are available for bridge owners that may be useful in the design and construction (as well as maintenance and rehabilitation) of various types of off-system bridges. Although not specifically described herein, nor included in the reference list, a vast number of electronic and print resources are readily available that provide guidance in everything from foundation design, bridge inspection and rehabilitation, bridge hydraulics, and other areas. One of the most important sources of information is the state Local Technical Assistance Program centers. Many of these centers maintain extensive lending libraries of print and electronic media freely available for loan. Additionally, staff engineers are available to provide advice and assistance on various topics. Three significant on-line sources of information were found during the course of this investigation: The USACE, U.S. Navy Facilities Command (NAVFAC), and FHWA.

The USACE has numerous design guides that are simply written yet comprehensive. They include references concerning the geotechnical and structural design of footings, sheet piles, and cofferdams, and manuals on fixed-bridge design, inspection, and rehabilitation. These manuals are readily available from the USACE website. The NAVFAC manuals are similar in coverage and are also easily downloaded and printed from the NAVFAC website. The FHWA has numerous on-line (and print) design references that are readily obtained. These include design guidelines for geotechnical and substructure design and a large number of *Hydraulic Engineering Circulars* (e.g., HEC 18) related to stream and river hydraulics, hydrology, design for scour, and others. Additional references are available from other federal bureaus, such as the Bureau of Reclamation, which publishes an extremely comprehensive manual on the repair of reinforced concrete, which also may be downloaded. These references individually and collectively provide a significant base of reliable information for design engineers.

With the substantial increase in the use of the Internet and World Wide Web as repositories of information, it is anticipated that there are many references and sources of information that were not found during the preparation of this synthesis. Interested parties will likely search for information as needs arise. No attempt to characterize all of the available information would be sufficient. Users are simply encouraged to consider this valuable resource when in need of assistance.

Software

The engineering community has changed markedly through the years, with one of these ways being the proliferation of software as a replacement for rote hand calculations. Automation can increase both the speed and accuracy of routine calculations. For small agencies in particular, their ability to engineer, produce plans, manage inventories, compute estimates, project schedules, and many other functions can be enhanced by automation. Software allows for the creation of rapid "what-ifs" in the selection of bridge types for replacement, which can then be cost-estimated for purposes of determining the economical choice.

A brief description of some of the software tools available for local agency bridge owners follows. It is by no means an exhaustive summary, because a large percentage of software presumably exists only in the hands of the owner/developer such as programs, spreadsheets, etc., developed by engineers for their own use or the use of their agency. The information presented herein was that mentioned by survey respondents or discovered during the literature review process of this synthesis.

Engineering software can take many forms. It may be commercially available programs developed for sale to government and private consultants alike. This software is generally regularly updated and runs the gamut from general purpose structural analysis and design programs to very specific stand-alone programs that do one or only a few things. In addition to commercial software is the category of software developed by state agencies for use by in-house staff and contract employees performing work on their behalf. This software is frequently available for download from a state website for free or for nominal charges. The final type of software is that which is most difficult to document and that is the proliferation of spreadsheets, custom programs, MathCAD sheets, etc., which are used by various agencies and consultants throughout the country. Some of this information can be found on-line.

One of the trends noticed in the preparation of this synthesis was the amount of software available for free or a nominal charge on the World Wide Web. A summary of these programs is presented in Appendix B. The vast majority of the software pertains to structural engineering calculations. However, a review of the material in Appendix B will show that free software is also available for various other disciplines such as geotechnical engineering, hydraulics, and coordinate geometry, among others. A large amount of software is available from various FHWA websites and this software is catalogued here.

One source of software not discussed in Appendix B is the engineering software previously noted that is available from PennDOT. A large amount of software has been developed through the years by the department under contract with various consulting firms covering a great range of topics, including bridge rating, steel and prestressed concrete girder analysis and design, abutment and wingwall design, elastomeric bearing design, pier design, box culvert analysis and design, floor beam analysis and rating, bridge geometry programs, and others. The programs are available in both the AASHTO *Standard Specifications* and LRFD versions and depending on the software version can work in either US or US and SI units (International System of Units). A complete list of software is available on-line from the PennDOT website. It is conditionally free—that is, it is available for free to other government agencies, including support, and is sold for a nominal fee to private industry.

As a design expedient, PennDOT has also developed the BRADD (Bridge Automated Drafting and Design) program. This program guides the user through a series of input screens that branch and are context-sensitive to the type of bridge being designed. The result of the process is a completed design for an entire single-span bridge (the program is limited to single-span bridges and culverts), as well as a complete set of engineering drawings that are automatically created as part of the design process. This program has been in use for a number of years and replaces many of the PennDOT BLCs discussed previously in this chapter. The program has been used most effectively to design bridges on behalf of local agencies and has been used by consultants working for PennDOT under emergency contracts to replace several bridges washed out by Hurricane Floyd in the late 1990s.

Concrete Bridge Software

Two programs, Computer Program for Box Culvert Design and Optimization (CUDO 1986) and Design of Continuous Reinforced Concrete Slab Superstructures for Bridges (SLABBRDG 1993) are available from CRSI.

The CUDO program was developed for the analysis and design of CIP box culverts having from one to five cells and under varying fill heights. The program is only for structural purposes; hydraulic analysis is done separately. This program has the capability for computing optimum culvert designs that balance the costs of reinforcing, concrete, and formwork. CUDO can design a culvert with an optimum number of cells and an element thickness based on least material cost or can analyze existing configurations. Factors such as excavation and backfill differences between options, implications of staged construction, etc., are not included; however, they are important considerations that must be considered by the engineer.

Limitations of the program include minimum and maximum span lengths (of the slab) ranging from 1.5 to 7.6 m (5 to 25 ft), although it is indicated that neither of these extremes represent efficient or cost-effective designs. The design loading can be any combination of three point loads that move across the structure. In lieu of specific point loads being input, a standard MS 18 (HS 20) vehicle is used. Fill heights can vary and the program considers the depth of fill in the distribution of live load to the culvert slab and for the consideration of impact. The program uses an equivalent fluid pressure of 8.5 kN/m^3 (54 pcf) in lieu of other information. The user is able to enter a coefficient of active earth pressure to meet the specific backfill to be supplied for the installation.

For the optimization option, the width of the total opening is input and the program analyzes various single and multi-cell options to determine the least total cost, although for a specified configuration, fixed geometry is input and the program determines forces and reinforcing steel requirements. Output consists of recommended member thickness and reinforcing size and spacing. If the optimization option is chosen, the best option for each number of cells is listed so that the engineer has the prerogative of selecting a slightly more expensive option that better satisfies some other project constraints.

The CRSI SLABBRDG program is used for the design of continuous concrete slab bridges having between two and five spans. The program considers constant depth slabs, slabs with haunches, and slabs with constant depth drop panels. Asymmetric layouts are easily accommodated.

The program designs for a series of one to three moving loads using the AASHTO *Standard Specifications*; lane loading is not accommodated. The program designs using the LFD design method, with required serviceability checks for crack width and fatigue of reinforcing steel. All of the load factors, load combinations, member strengths, and allowable stresses are in accordance with AASHTO, although the user has the flexibility to change some of the defaults. Input for the program is very simple, requiring only several screens of input to define the bridge geometry, material properties, and live and additional dead loads.

Output from the program is concise and similarly easy to use. Depending on the number of output points chosen by the user (typically tenth points are used in design), the moments, required reinforcing for strength, serviceability checks, suggested bar spacings including the increased steel for the slab edge beam, and finally the substructure reaction forces, total DL, LL+I per foot of lane, and factored shear forces are listed in simple tables. The output is in a similar form for the constant depth, haunched, and drop panel options. Longitudinal and transverse reinforcing size and spacing are presented for both top and bottom mats.

Steel Bridge Software

A supplement to the AISI *Standard Plans* is the AISIBEAM software (AISIBEAM 2000). Presently limited to the design of single-span bridges using the AASHTO

Standard Specifications, the software is an extension of the standard plans and allows for the design of bridges of almost any width and length with user-specified dimensions. Additionally, the program can be used to compute the inventory and operating ratings of existing steel structures. The additional flexibility provided by the program is the ability to design or rate structures using a user-specified vehicle with axle loads and spacing input at the user's discretion. The flexibility provided by this option allows for the examination of existing steel structures to carry specific vehicles (fire trucks, concrete mixers, logging equipment, etc.) or allows for the design of new bridges using the same user-defined vehicles. This is a benefit to local agencies that may want to consider the ability of a bridge to carry specific vehicles known to operate in the vicinity of the structure. The software, as well as digitized versions of the standard plans (no longer available in print form), are available for download for a 30-day free trial from AISI, after which a nominal fee is charged.

The combination of the AISI standard plans and software provides significant reductions in engineering design effort, especially for agencies with no comparable steel beam design software. Additionally, they are an effective replacement for the older FHWA standard bridge plans and allow for the selection of several options for most short-to-medium-span bridge replacements.

Alternatives Analysis and Life-Cycle Cost Estimating

A tool that has become more frequently used in recent years in all areas of infrastructure and capital equipment management is life-cycle costing—an accounting methodology for analyzing the implications of various financial decisions. Simple examples of life-cycle costing include buy versus lease decisions for equipment and repair versus replace decisions for infrastructure upgrading. Each of these decisions has financial consequences, not all of which can be determined by an examination of first cost alone. LCC allows for a systematic examination of the various costs of a project including its initial cost, future maintenance expenses and their time of occurrence, as well as disposal and reconstruction costs. A software tool, the Bridge Life Cycle Costing program, Bridge LCC, has been developed by the National Institute of Standards and Technology for LCC of bridge structures. The program and manual are available for download free of charge from the organization's website. Originally developed as a tool to help evaluate the economic differences between conventional construction and innovative material projects, the program has a host of capabilities that allow for the making of informed financial decisions.

The fundamental operation of the program can occur in either a "Basic" or an "Advanced" mode. In Basic mode, the user enters data for both a base scenario and for up to five alternatives. The Basic mode is typically used when the first costs and future costs are known with some certainty. In this mode a standard financial analysis of the various alternatives is completed and they are reduced to an equivalent first cost. In the Advanced mode, the costs need not be known to the same degree of certainty. One of the strengths of the Advanced mode is its ability to model uncertainty in some or all of the cost items. Results of the analysis will then be reduced to probabilistic costs based on Monte Carlo simulations that produce anticipated lowest and highest costs (per alternate) reflecting the degree of uncertainty in the input variables. This sensitivity analysis is valuable if the costs are not accurately known and can only be projected to be in a given range. This is likely the case for unusual types of construction, new materials, or for the estimation of future maintenance or disposal costs.

The use of the software begins with the input of general information describing the situation. For purposes of financial analysis, the base year, analysis period, inflation rate, and discount rate need to be specified. The basic input wizard proceeds to gather characterizing information describing the alternatives. This information includes the number of lanes on and under the bridge, bridge deck area, and bridge length. These values are used to compare the costs of the alternatives on a cost per unit area or unit length basis. Additional information requested includes lump sum construction costs; operation, maintenance, and repair costs; time period between repairs; and disposal costs. Based on this initial information, a quick analysis of the situation is completed.

The advanced analysis features allow for significant expansion of the programs' capabilities. For instance, costs can be entered for commonly recognized elements such as deck, superstructure, and substructure if known, in lieu of lump sum bridge costs. Cost items can be specifically broken down by several criteria. A number of costs can be created, all of which are associated with an event. For instance, costs for a repainting job can include blasting, containment, repainting, and disposal, all of which are tied to the event of painting. Each of the component costs can be specified as well as their individual uncertainties. The cost can also be assigned to a specific bearer; that is, the owner, user, or third party entity, so that the cost to each bearer can be tracked. Graphs of LCCs by component, bearer, or simply total cost can be displayed. A project may be deemed more or less attractive to an owner depending on what costs can be minimized and the percentage of the cost that must be covered by the owner.

In addition to material costs, the program has the ability to model user costs, specifically user costs associated with lane closures and workzone impedances. Based on input data that can include speeds in the workzone, accident rates, driver costs, vehicle operating costs, accident costs, and others, rehabilitation and replacement options that require various workzone lane closures can be explored. The construction costs can be considered along with user costs in selecting an optimum solution. Again, one might select the least total cost project or examine alternatives that require greater construction funds but maximize safety and minimize user costs. Some of the cost items may be difficult to determine, specifically some of the lane closure and user costs. These may not be of great importance in many off-system bridge projects; however, the ability to systematically determine their influence on the overall financial picture is a valuable option for potential users of the software.

CHAPTER FIVE

OFF-SYSTEM BRIDGE ADMINISTRATIVE ASPECTS

This chapter focuses on the administrative processes involved in the maintenance, rehabilitation, and replacement of off-system bridges. These processes include various concerns such as bridge management and the development of effective mechanisms for planning bridge maintenance, rehabilitation, and replacement activities; bridge financing using the various federal, state, and local funding mechanisms; and the environmental permitting process and its significant impact on the engineering and construction process. Information gathered from the project questionnaire and literature search was reviewed to accurately portray the administrative aspects of off-system bridge management. The chapter begins with a brief description of the project survey results.

The opinions of local bridge owners were sought regarding the various administrative challenges in managing their bridge infrastructures. As might be expected, a number of the responses commented on the burden of federal and state regulations with regard to design standards, funding conditions, and environmental regulations. Although design standards are addressed separately in this report, comments were provided indicating the need for revised design guidelines for low-volume roads and their bridges.

Several comments regarding funding arrangements were presented. One of the local agency responses from Iowa commented on a provision of state law that places a cap of $50,000 on the work allowed to be performed with in-house employees. The local agency found that the cost of similar work, if let as a contract, results in price increases of 50%. The agencies comment was that more work per dollar could be accomplished if the cap on project amount was raised or eliminated. Because of the cap, inflated contract prices limit the total amount of work that the agency can accomplish. Along the same lines, comments were presented that the time required to advertise a project, select contractors, and grant a notice to proceed was excessive and hampered the ability to effectively execute required work.

ADMINISTRATIVE PROBLEMS

A significant problem for local agency bridge managers is the management of the infrastructure under their control. The combination of limited budgets, large systems, small staffs, lack of experience owing to retirements and the inability to attract new employees, and occasionally incomplete or disjointed record keeping result in difficulties in programming work in an efficient and systematic fashion. In addition to these local difficulties in project programming are the administrative challenges of managing engineering design, permitting, construction, etc., with these same small and inexperienced staffs. These issues will be explored here.

Asset, Resource, and System Management

One of the concepts being promoted as a powerful tool in the management of transportation infrastructure is asset management. Asset management involves a blend of economic and engineering information to help prioritize and select maintenance, rehabilitation, and replacement alternatives. It allows for various competing options to be evaluated on an objective basis. Additionally, it allows for fact-based decisions to be made with regard to proposed expenditures and is used as a measure of accountability. The effective use of asset management principles is expected to lead to higher-quality total systems.

The combination of public expectations for high-quality transportation, difficult budgetary demands, necessary accountability for decisions, and the availability of advanced technology and “what if” scenario modeling have both necessitated and allowed for asset management to develop. In 1999, the FHWA Office of Asset Management published an *Asset Management Primer* to assist transportation infrastructure owners and managers in the prioritizing of expenditures for transportation improvements. Although touted primarily as a tool for state highway agencies, many of the asset management concepts could be applied by local agencies on a different scale. Similarly, with the vast population of bridges being lower-volume and off-system bridges, asset management, even employed by the states, should help prioritize expenditures on all classes of infrastructure.

Asset management is a more refined method of prioritizing work than has previously existed. Although well-intentioned, past and in many cases current practices still rely heavily on subjective criteria, “gut feelings,” political pressures, and personal preferences; little is based on objective techniques grounded in analytical concepts. The “worst first” concept of finding the worst performing features and fixing them is the common solution. Success is traditionally measured in managing the backlog of work and not in improving the overall sufficiency of the system or in maximizing the impact of available resources.

Some of the impetus toward implementation of asset management comes from the 1991 ISTEA legislation. This bill required that each state develop a statewide transportation plan that predicts the growth of all modes of transportation. A part of the statewide plan is also management of existing assets, including the monitoring, maintenance, and rehabilitation of the current system. In addition to the long-range statewide plan is the short-range STIP, a financially realistic plan for funding improvements in the near future. This plan should consider both anticipated costs as well as the source of the funding.

It is reasonable to assume that asset management might be used in formulating both the long-range plan and more importantly the STIP. Many states currently have some of the components of a total asset management system (AMS), notably pavement management or bridge management systems (BMS); however, these systems are neither fully developed, uniform, or completely capable of all the needs of the complete AMS system approach. With respect to BMSs, the *Asset Management Primer* indicates that the most prevalent one in use is the PONTIS system. PONTIS, which is capable of inventorying existing structure condition data and interpreting engineering and economic models, can be used to identify the optimal maintenance strategies considering the potential costs and benefits. It was reported at the time of the writing of the FHWA report that 37 states had implemented PONTIS and another 2 a competing system named BRIDGIT. Very few of the states use the BMS programs for decision making, because of the inherent difficulty in acquiring the types of information needed; for instance, bridge component condition surveys and accurate historical cost data for common maintenance and rehabilitation tasks.

As states have begun to recognize the need for asset management, many have begun to move in that direction. However, the realities of effective implementation are that a completely integrated AMS is difficult to achieve. There is inconsistent or nonexistent input information in some respects and the collection of accurate input data may be expensive, time consuming, or both. In addition, practical considerations and institutional, political, or community pressures may still short circuit the process. Finding trained staff able to work comfortably with the statistical modeling process, especially analysts able to work equally well in engineering and program management, is a challenge. An additional complication is the lack of integration among the various management systems in an agency such as the stand-alone pavement and BMSs. A comprehensive system able to look at pavement versus bridge spending is required to look at total asset management across the entire road network.

A survey of rural road-user perceptions of road and bridge needs is summarized in Hough et al. (1997b). Comprising more than 1,200 responses from a diverse mix of rural road users (commuters, farmers, mail carriers, school bus drivers, and road superintendents), the objective of the survey was to assist decision makers in allocating resources to an extensive rural road network in North Dakota. The top five road improvements requested by the respondents were (1) more and better gravel, (2) more paved roads, (3) wider roads and shoulders, (4) build roads up, and (5) replace and widen bridges. One of the foremost operational improvements cited was the increased use of guardrails on bridges. The surveyed individuals were also questioned about mechanisms to increase roadway funding. Approximately two-thirds of the respondents supported an increase in taxes, essentially in the form of a sales tax or a fuel tax, with a small percentage in support of increased real estate taxes.

In 1997, FHWA Region 8 conducted a workshop in Rapid City, South Dakota, to discuss the current practices of local agencies with respect to maximizing their available resources for transportation projects. Various local agency representatives, FHWA participants, LTAP coordinators, and other interested parties were in attendance. A listing of the topics discussed and approaches currently being used are found in STRETCH (“STRETCH Local Agency Funds” 1997); however, only brief synopses are provided. Contact names are presented for those interested in inquiring about a particular topic in more detail. The major topics covered were financing, procedural, legislative, manpower, equipment, materials, and resources. A brief discussion of some of the more interesting items from some of the topic areas is presented here.

- Procedural—Areas studied included a comparison of contractor costs versus those incurred in-house for construction work. Additionally, it was noted that local South Dakota agencies were experiencing significant cost savings by funding projects locally and eliminating federal requirements. Additional topics of discussion included design–build, standardized design plans, transportation planning, flexible design standards, the conversion of low-volume paved roads to gravel, and project administration.
- Legislative—Topics explored included the consolidation of local governments to leverage resources, privatization or closure of low-volume roads, better enforcement of load limits, elimination of Davis–Bacon requirements for locally funded projects, and establishment of realistic Disadvantaged Business Enterprise goals for local projects.

Among the methods suggested as being effective in maximizing the usefulness of funds available to local road agencies is the reduction of maintenance or closure of some roads and associated bridges. Although the deference of maintenance is a prime contributor to the current state of the bridge population, there are cases in which funds are simply not available to meet current demands. Difficult decisions are frequently made regarding the ability to keep a deteriorated facility open. Welte et al. (1997) provided a summary of a more detailed report on the legal implications of deferred maintenance and road closure as a potential liability issue for bridge owners. Their report specifically addresses the nuances of state law in North Dakota; however, the decisions they refer to in lawsuits are from federal court rulings.

In general, Welte et al. indicated that government agencies are immune from lawsuits arising from deferred maintenance or road closures as long as the actions they took were considered discretionary; that is, the decision made to defer maintenance, close a bridge, or post a warning sign was not explicitly prohibited by statute. The possibility that actions will be considered discretionary in a court of law increases if an agency follows applicable statutes, presents a good faith effort to minimize public risk, and uses factors other than pure economics to make maintenance decisions; that is, historical levels of maintenance and repair for a particular infrastructure component.

In 1989, Baumel et al. discussed the deteriorating state of rural roads and bridges. The authors advocated alternative investment strategies as a means of maintaining quality of service with limited budgets. The study focused on changing the extent of service versus the anticipated user costs of inconvenience. The three study areas, each of approximately 260 km^2 (100 mi^2), were located in three distinctly different rural Iowa counties. Several investment strategies were studied including

- Abandoning county roads with no residential access,
- Converting continuous public roads to private drives,
- Paving selected gravel roads and abandoning those with no residential access,
- Converting roads with no residential access to limited maintenance facilities,
- Converting dead-end roads to private drives,
- Converting paved roads to gravel roads, and
- Upgrading only selected bridges to legal load limits.

The nature of the deterioration of rural public roads is derived primarily from the weights and frequency of use of rural roads by heavy agricultural vehicles, a significant problem in rural states such as Iowa with large numbers of unpaved roads. In earlier times, most rural roads served private residences; however, because of the expansion of farm size vis-à-vis the acquisition of multiple parcels by a single land owner, many roads no longer serve residences but are only required for field access.

Baumel et al. went on to cite a survey of rural road users that concluded that the combination of heavy vehicles on unpaved roads was a significant problem with respect to road durability, ride quality, and dust control. Road widths (and bridge widths) are inadequate for modern agricultural and commercial vehicles and narrow lanes in general create safety problems. Baumel also discussed the high number of deficient bridges on the rural road network and proposed that using only NBI data understated the problem, because there are numerous structures less than 6.1 m (20 ft.) in length that are deficient but not catalogued in the NBI data.

The rural road problem generally is the result of inadequate funding for an extensive network of roads. Eight alternative funding solutions were described by Baumel et al. (1989) with several discussed here.

- Legislate large increases in state and federal funding—Baumel reports on the political realities and difficulties of asking for extensive tax increases to cover needed road reconstruction costs. Although the ISTEA and TEA-21 bills have had significant impacts, there are still pervasive problems on the road and bridge network and large increases in federal and state taxes are unlikely.
- Impose local option taxes and local bonding authority—This option involves giving local agencies increased flexibility to enact taxes and engage the financial markets in the form of bond issuance.
- Reduce minimum construction standards for rural roads and bridges—The reduction in minimum design loads, geometric criteria, and maintenance standards is discussed as a potential cost-saving measure in terms of reducing the first cost of bridge and road construction and maintenance. However, it is also noted that lower standards may result in higher maintenance costs, shorter expected life, and other increases in total LCC.
- Abandon road segments with no residential access requirements—The extensive rural road network in Iowa (the study area) is basically laid out on a square grid, 1.6 km (1 mi) on a side. This extensive network was once dotted with numerous small farms, churches, schools, and other rural facilities, many of which have been eliminated or consolidated through the years. A reduction in the number of rural roads through abandonment will focus the resources on the more effective maintenance, rehabilitation, and reconstruction of truly vital roads instead of diluting the resources across a vast network.

Baumel et al. (1989) admitted that there are significant public policy implications from many of the suggestions and that they might not all be politically viable. However, given the budgetary pressures and amount of work that needs to be done, tough choices may be assisted by considering some of these alternate investment strategies.

In conjunction with the concept of asset management are new changes in accounting principles that will have pronounced effects on the administration of local roads. Of particular importance to local agencies are the requirements of Governmental Accounting Standards Board (GASB) Statement 34 as it relates to the management of infrastructure investments ("What's GASB 34 . . ." 2000). The GASB Statement 34 requires a change in accounting practices regarding the treatment of infrastructure assets.

With traditional cash accounting methods, infrastructure expenses are treated as a cash expenditure in the year incurred. However, the infrastructure investment is not treated as an asset on future financial statements and its present value or depreciation is also not considered. Infrastructure such as roads and bridges are essentially "off the books." With the issuance of GASB Statement 34, accrual accounting methods are now required so that infrastructure is treated as a depreciable asset over some time period and its change in value as a result of deterioration or repair is tracked. This method of accounting is similar to that used by private businesses for the management of equipment and fixed assets.

The intent of the GASB 34 policy is to provide for a more complete picture of a public agency's financial health. The requirement to annually report the value of public assets should result in more responsible management of fixed infrastructure, because the condition of these elements, in relation to the currently reported value, will be a matter of public record. The requirements for reporting were to be phased in from June 2001 for agencies with more than $100 million in annual revenue to June 2003 for agencies with less than $10 million in annual revenue. In the first year of required compliance, only newly constructed assets need be reported, whereas over a 4-year period, all existing assets must be brought into the financial reports.

As part of a reference described herein ("What's GASB 34 . . ." 2000), a survey of Iowa counties was conducted to determine the impact of the GASB 34 procedures. Some local government respondents indicated that the GASB 34 requirements were not a burden because they maintain accurate records of current inventory and costs, whereas others perceived the new standards as an unfunded mandate.

Bridge Management

One of the components to effective management of bridge infrastructure is the BMS. BMS systems are a database of bridge conditions as recorded in the biennial SI&A inspections. They may also contain additional information such as the findings of element inspections. BMSs might be used for bridge programming or be more completely integrated into more comprehensive AMSs, as discussed previously. Typically, BMS systems are maintained at the state level as part of their requirement to comply with federal reporting requirements. However, these systems are often complex and may not always be accessible to local agencies.

Gralund and Puckett (1996) discussed the development of BMS tools of appropriate depth and complexity for their effective use by owners of small bridge populations. Traditional BMS systems such as PONTIS are geared toward state or large network level management, where tracking of deterioration and historical data can be used to maximum potential. On smaller systems, where the historical deterioration and cost data do not necessarily exist in the depth or breadth required of the larger BMS models, an alternative approach is warranted. A description of the development of a BMS for Wyoming is presented here.

After reviewing systems used by other states and the PONTIS system, the best features were selected for the development of a local agency BMS for Wyoming. A two-part system was developed; a series of modules for inventorying structure data and a second part for prioritizing needed work. Several models were considered for prioritizing work, including the sufficiency rating model, the deficiency rating model, the time-dependent deterioration model, and a combined deterioration rate and deficiency point model.

Use of the sufficiency rating alone is noted as having serious shortcomings because it is so heavily weighted on load capacity and deck width. This heavy weighting may indicate an inadequate bridge (low sufficiency rating); however, depending on the location of the bridge, it may be sufficient for the traffic demands.

The deficiency rating model is a cumulative point rating, an inverse of the sufficiency rating. A 100-point rating indicates a bridge on the verge of collapse. The primary shortcoming of the deficiency model is that it treats the entire bridge as a whole without regard to elemental rankings. Gralund and Puckett (1996) commented that an expansion of the deficiency point model to the element level would be a significant improvement.

The deterioration models are all based on the ability to accurately predict how an element with a current ranking will deteriorate over a given time. The best way to estimate the probability of deterioration in a given time period is to have a historical database of deterioration rates. Most agencies either do not have these data or what they do have is not systematically stored; therefore, the use of predictive deterioration modeling requires more judgment than actual data-based science.

For the Wyoming BMS, the deficiency point model was selected because the sufficiency point model does not allow for accurate prediction of maintenance needs and the deterioration models rely on data not currently available. Weighting factors are assigned to the various computations; they can be changed to reflect user preferences, that is, more emphasis on clearance as opposed to deck width or vice versa. In addition to deficiency points for the entire structure, deficiency points are also calculated for a number of standard components of a bridge. In this way, the effects of deterioration on certain key elements can also be used as flags for prioritization of maintenance and rehabilitation activities even though they may have little impact on the equations used to compute the structures' overall deficiency points.

The BMS just described is recommended for use by local agencies in lieu of the more comprehensive PONTIS network management tools. Gralund and Puckett indicated that this BMS could be used by small agencies such as those administering fewer than 150 bridges, although for larger bridge populations, PONTIS should be considered. Before implementing one of these systems, the economic impacts should be considered in terms of the software costs and manpower required to operate the two different systems.

OFF-SYSTEM BRIDGE FUNDING

A number of funding sources are available to local agencies. Some of these could be considered innovative, such as the use of a soft match program whereby eligible local agency costs on noneligible work can be used to offset the agencies expected contribution on matching fund projects or the participation in State Infrastructure Bank (SIB) programs. The agencies contacted during the project survey were asked to comment on current funding arrangements including innovative funding. A summary of the responses follows.

Generally, all of the responses indicated that the current federal funding programs are of great assistance, but that more money is desired. Several suggestions were made relative to flexibility in spending for maintenance projects and for fully funding preliminary engineering costs and bridge inspection. Local agencies requested that in-house development costs be considered reimbursable expenses. In addition, there were specific requests for a greater portion of available funds to be made accessible for off-system and low-volume road bridges. For measures that are not specifically funding related but have implications for future expenditures, there was mention of an increased need to support development of new materials and technologies.

Federal Programs

A number of federal programs have as their main focus the funding of transportation improvements. The FHWA has published a guide to these programs, *A Guide to Federal-Aid Programs and Projects* (1999). The guide presents a brief description of each program, its funding levels, restrictions on use, intended benefits, statutory reference, and other pieces of valuable information.

Highway Bridge Replacement and Rehabilitation Program

The Highway Bridge Replacement and Rehabilitation Program (HBRRP) {23 USC 144 and 23 CFR 650D} is a federal program that draws resources from the highway trust fund to specifically target bridges in need of rehabilitation or replacement (*Federal Aid Policy Guide* . . . 1994). Funds have traditionally been restricted for use in the total replacement or rehabilitation of a bridge on any public road. However, a recent memorandum from the FHWA (2002) indicated that HBRRP funds may be used for preventative maintenance of bridges on Federal-Aid Highways (local roads and rural collectors are excluded). It must be emphasized that routine maintenance is excluded from HBRRP funding; only those activities that can be demonstrated as extending the useful life of a structure may be funded under the HBRRP. Additionally, the selection of projects available for matching funds must be done through a systematic application of a BMS.

The HBRRP program has a provision that specifically designates no less than 15% of a states' allotment to be used for off-system bridges; that is, those in the federal definition that are not on Federal-Aid Highways. These include bridges on the rural local, rural minor collector, and urban local systems. Additionally, 20% of a states' allotment may be used either on- or off-system. The remaining 65% is explicitly restricted to on-system activities. The HBRRP has a provision that allows for the expenditure of local funds on off-system projects to be counted at 80% of their cost toward the states' share of eligible costs for other HBRRP projects. This flexible matching (soft match program) allows for local funding of noncontroversial projects that are acceptable to the local agencies (the majority of these expenses can be counted as the local match on another HBRRP eligible project). The funding available under the TEA-21 reauthorized HBRRP increased from $2.94 billion in 1998 to $3.62 billion in 2003 ("HBRPP Fact Sheet . . ." 1998).

For local match programs, a survey of state DOT websites revealed several states with on-line versions of guidance documents discussing the process and rules for soft match participation. An example of this is Nebraska and the Nebraska Department of Roads. The Nebraska Department of Roads website contains a copy of the *Soft Match Bridge Program Policies* (2000), which clearly establishes the process by which the state will work with local counties to ensure that proper credit is received for eligible work. Included in the document are comprehensive descriptions of eligible bridges and eligible expenses, a description of soft match procedures, and guidelines for soft match projects including required engineering objectives, along with samples of letters of application, certificates of compliance, and examples of the required information on bridge plans.

For off-system HBRRP projects, the TxDOT uses state funds for one-half of the required 20% match, with the result being that local agencies are only required to participate at a 10% level. In addition, Texas waives the required 10% local contribution as long as the local agencies agree to perform an equal dollar value amount of structural improvement or safety work on other bridges or drainage culverts. Therefore, it is possible through this agreement for the state to provide the entire 20% match for off-system HBRRP bridge projects.

Surface Transportation Program

The Surface Transportation Program (STP) {23 USC 133} was established in 1991 as part of the ISTEA legislation. The STP replaced the previously administered Secondary Roads program. Authorization of the STP program was continued by the TEA-21 legislation enacted in 1998. Funds for the STP were authorized for the period of 1998–2003 under the TEA-21 legislation and ranged from approximately $4.8 billion in 1998 to an estimated $5.9 billion in 2003. Funds from the STP may be used for a broad class of transportation improvements including bridge construction, reconstruction, rehabilitation, restoration, and improvement. These activities can include seismic restoration and painting. Funds are generally limited to Federal-Aid Highways for roadway projects; however, any bridge on a public road is eligible for STP funds. The funding split is a traditional 80% federal/20% local match for all projects except for Interstate highways where the percentage of federal share may be greater. For the off-system roads considered in this synthesis, the 80/20 match is the usual mix of funds. Total funds are divided into several set-aside areas. Of the total funds obligated to a state, 10% are earmarked for safety improvements, an additional 10% for transportation enhancements (environmental activities), 50% are divided between urban and rural areas, and the remaining 30% may be used at the states discretion.

In examining the use of STP funds for non-NHS system bridge construction, it was determined that STP funds were used in fiscal year 1999 to address problems on 959 bridges, with total obligated federal funds of approximately $174 million. The total STP funding for non-NHS projects was approximately $3.7 billion; thus, bridge expenses were approximately 4.7% of the total STP funding of non-NHS projects, indicating that bridge projects are not a significant portion of the STP program budget.

Innovative Bridge Research and Construction Program

Although only a small portion of the total federal dollars available for bridge construction, the FHWA Innovative Bridge Research and Construction Program (IBRC) is an important source of funds in terms of its potential impact on future bridges, including design, construction, maintenance, and rehabilitation. Authorized as part of the TEA-21 legislation, the IBRC program provides a nominal amount of funding, $1 million per year for the 6-year TEA-21 authorization for research on innovative materials, and a total of $102 million over the same period for construction activities. Owing to the innovative nature of the projects, the goal was to fund as many of the projects as possible with a 100% federal share, although the actual federal expense is at the discretion of the FHWA. The funds may also be used for proprietary products provided the proprietary nature of the product is clearly identified. The monies may only be used to offset the innovative features of the project. To qualify for IBRC funds, a project must meet one of the following criteria:

- Development of new cost-effective, innovative material for highway bridge applications;
- Reduction in maintenance or LCCs, including those costs of construction;
- Development of construction techniques that increase safety and minimize disruptions;
- Development of engineering design criteria for innovative materials;
- Development of innovative and cost-effective measures to separate vehicular from railroad traffic;
- Development of bridges that are more apt to sustain the effects of natural disasters; and
- Development of new nondestructive evaluation methods.

To obligate funds each year, the FHWA obtains candidate projects from the states, which in turn may coordinate with local agencies to find locations that are appropriate for the proposed innovative solutions.

Although the IBRC is a small source of funds, it partially funds a large number of projects each year, because the monies are only used to offset the costs associated with the use of the innovative materials (funding does not include the costs of the conventional portion of a project). Many of the projects funded under the IBRC program include the use of advanced composite materials, the use of innovative metallic blends for enhanced corrosion properties, and the use of high-performance steel and concrete in bridge construction.

State and Local Programs and Innovative Finance Techniques

Although federal aid always receives significant coverage when highway financing is discussed, statistics indicate that of the approximately $101 billion spent on highway construction in 1997, federal aid amounted to only 21% of the total funds expended on transportation. The balance of the funding was 52% state and 27% local. A more complete discussion of current funding levels is presented in chapter two. The focus of this discussion is to present material regarding the funding mechanisms, including innovative techniques, being used by state and local agencies to maximize the impact of their efforts.

State Initiatives

The 1995 National Highway System Designation Act established a new mechanism for the financing of both state and local road improvement projects, the SIB. The FHWA describes the program in the *State Infrastructure Bank Primer*. In its simplest form, the SIB program is a bank with initial seed money provided by a combination of federal and local governments that allows for innovative financing of various types of road improvements. The various financial programs that exist within the SIB program include loans, lines of credit, and debt service guarantees. This ensures that money lent to a particular project is repaid on a payment schedule and, upon repayment, goes back into circulation for use in subsequent projects. States are allowed to deposit certain portions of their Federal-Aid Highway funds into SIBs for seed money. They are required to contribute 25% of the federal portion or a total of 20% of the entire invested sum. Additional funds can be contributed beyond the federal match. Several states currently have SIB programs in place and Texas has an SIB manual available for local agencies (*State Infrastructure Bank* . . . 2000).

Because the funds from the SIB program can be used for almost any aspect of a transportation project, including preconstruction activities such as planning, studies, permitting, and engineering; highway construction and bond issuance; and transit system funding, projects can be accelerated. The TxDOT manual on the SIB program states

> Currently, TxDOT expects to be able to fund only about 36% of the needed transportation projects in Texas. TxDOT will continue to fund as many needed projects as possible. However, a project considered a very high priority by one community, may not be ranked high enough on a statewide basis to receive funding for several years. If the local community wants the project completed faster, it could borrow money from the SIB and advance the project by several years. Also, if the proposed transportation project would generate additional economic development, the local community may receive enough revenue from the increased tax base to easily pay the financial assistance from the SIB. Thus, the community could get its project completed much sooner with little or no additional costs.

The SIB program can be used to assist local communities, in particular those without the financial market access required to raise the funds for local improvements. Additionally, several local communities can pool their funds through the SIB program.

The SIB program demonstrates a strong state and local commitment to transportation improvements and can increase the attractiveness of particular projects to the private sector. This increases the possibility of private-sector funding or cost sharing on transportation projects. The strong commitment of locals and the state increases the likelihood of transportation-related economic development as well, which in turn strengthens the local economy through tax revenues.

It is anticipated that loans from SIBs will be the most common use of the program. Because the SIB at this time is still a small program, judicious use of the funds is necessary to leverage the impact of the program. One of the strongest impacts of the SIB funds is in providing working capital for portions of a project not usually funded otherwise. These activities are typically the preconstruction planning, permitting, and engineering design activities.

In addition to direct loans, indirect financial support is also available; so-called credit enhancement. Credit enhancement includes a series of benefits offered by SIBs intended to assist local agencies in pursuing the primary project funding in the open market. An example of credit enhancement is the extension of lines of credit to local agencies to illustrate credit worthiness to an independent financial institution. They also can be used as an emergency loan owing to unanticipated revenue shortfalls. In addition to lines of credit, debt service guarantees are also possible through the SIB program. Providing a debt service guarantee again makes a local agency more attractive to lenders, especially with respect to the issuance of bonds. A debt service guarantee can substantially improve the grade of bond to be issued, thus saving interest costs and improving the attractiveness of the bonds.

Although at present a pilot program in many states and likely to only be applied to a small percentage of projects, the SIB concept is one of several innovative financing tools available to local agencies through partnering at the state level.

TABLE 5
COUNTY ROAD FUNDING SOURCES (Hough et al. 1997a)

Funding Source	Positive Attributes	Negative Attributes
Significant Contributors (>5%)		
Sales tax	Consistent revenue, inflation sensitivity, ease of administration	Inequitable
Special ownership tax	Revenue certainty, inflation sensitivity, ease of collection	Unpopular with those purchasing taxed items, inequitable/regressive
Wheel tax	Dependable revenue, ease of collection	Flat fee, controversial, equity
Rural improvement and special assessment districts	Ease of collection, equitable taxation	Opposed by some district residents
Minor Contributors (<5%)		
Severance tax	High revenue potential, user equity, low administration costs	Only applies in areas with natural resources; may be sporadic
Bonds	Stable, county control	Reduced flexibility with future revenue
Cost participation	Counties share in costs and benefits	(none listed)
Traffic fines	Low administration fees	No certainty, inappropriate for low population areas
Telephone tax	Some revenue certainty	Funds easily redirected

Local Initiatives

Hough et al. (1997a) provided an excerpt of a more complete report on innovative financing methods used to offset the costs of rural road construction and operation. Alternative sources of funds were examined by a study group of eight north central states: Colorado, Iowa, Minnesota, Montana, North Dakota, South Dakota, Utah, and Wyoming. The criteria used to evaluate the innovative funding resources were ease of collection, revenue certainty, inflation sensitivity, public acceptance, and user equity.

Of the nine funding sources studied, four (sales tax, special ownership tax, wheel tax, and rural improvement and special assessment districts) were recommended as being able to contribute significantly (more than 5%) to a county's total road budget. An additional five options, severance tax, bonds, cost participation, traffic violations, and telephone tax, were thought to contribute less than 5% to a county road budget. The positive and negative attributes of each new funding source are presented in Table 5.

The sales tax is a uniform tax on all or a select class of goods purchased in a county. The special ownership tax provides a mechanism whereby only special classes of items (i.e., the luxury tax concept) are taxed. This tax, owing to the optional nature of the luxury purchases, is perceived as unreliable if the demand for the taxed item is not a given. The wheel tax, as administered for instance in South Dakota and reported on by Hough et al. (1997a), is a tax of $4 per tire with a $16 maximum per vehicle. Of the funds collected, the first $2 per wheel is dedicated to road and bridge maintenance, whereas the remainder is used to offset property taxes.

Rural improvement and special assessment districts are a concept primarily used in urban areas for revitalization efforts. They rely on special tax assessments on properties within specific geographic limits. The effect of these special assessment taxes can, in the case of rural areas, be used to offset the construction of infrastructure needed for community expansion.

The lesser quality revenue streams also contribute to the total funds available for highway and bridge construction. Severance taxes are based on the extraction of natural resources from a particular area. Bonds are a traditional funding mechanism used to raise short-term funds that require the set aside of future revenues to repay the principal and interest on the borrowed money. Cost participation involves partnering with other local agencies to, in essence, pool funds for the completion of projects that are mutually beneficial. The use of traffic fines is also considered as a revenue source, although in sparsely populated areas the density is not sufficient for this to be a reliable source of funds. Finally, the establishment of a telephone tax has been used in certain areas whereby the telephone utility is the vehicle for tax collection, with a certain portion of the funds being earmarked for highway and bridge improvements.

In addition to finding ways of generating revenue, a similarly important concept involves cost cutting as a means of stretching budgeted dollars. Hough et al. (1997a) discussed two types of cost cutting strategies: service strategies and management strategies. Service strategies are those that could be considered maintenance or asset management activities. They include considering such concepts as using chip seals and soil stabilizers, reducing levels of maintenance, narrowing roadways, converting paved roads to gravel, and closing roads and bridges. The management strategies are directed at more efficiently using the resources at hand and include such issues as consolidating equipment, reducing the number of employees and sharing county engineers, improving management practices, cost sharing, and performing cost–benefit analyses on each project.

ENVIRONMENTAL PROCESS

One of the more challenging aspects of local bridge administration and bridge administration in general is successful navigation through the environmental process. An important part of the bridge engineering, rehabilitation, and replacement process, environmental permitting is required by various federal, state, and local statutes to safeguard various components of the natural and built environment. Much of the information presented in this discussion is based on the FHWA's *Environmental Guidebook* (1999), which is a compilation of various binding regulations, guidance memorandums, instructions for permit applications, and various documents related to the requirements for permits and compliance with environmental regulations.

The foundation for the environmental process through which transportation projects are approved is the National Environmental Policy Act (NEPA) enacted in 1969. In this act, protection of the environment was deemed to be in the nation's interest and specific requirements relative to the identification of potential impacts, listing of unavoidable adverse impacts, and the study of alternatives were delineated. In addition to the NEPA requirements, a large number of regulations covering various aspects of the natural and built environment have been enacted through the years. In a document prepared by FHWA, *Summary of Environmental Legislation Affecting Transportation—December 1998*, the federal regulations are divided into six major categories: General Environmental Statutes, Health, Historical and Archaeological Preservation, Land and Water Usage, Air Quality, and Water Quality. Within each of these six major categories are numerous pieces of legislation. A summary of the pieces of environmental legislation affecting transportation projects, taken from the FHWA *Summary,* is presented here.

- General Environmental Statutes
    - National Environmental Policy Act (NEPA)
    - Section 4(f) of the Department of Transportation Act
    - Economic, social, and environmental effects
    - Uniform Relocation Assistance and Real Property Acquisition Act of 1970
    - Title VI of the Civil Rights Act of 1964
    - Americans with Disabilities Act
    - Executive Order 12898: Environmental Justice
    - Public Hearings: 23 USC 128
    - Surface Transportation Act of 1987: Section 123(f) Historic Bridges
    - Wildflowers 23 USC 319
    - Highway Beautification Act of 1965.
- Health
    - Safe Drinking Water Act
    - Solid Waste Disposal Act
    - Federal Insecticide, Fungicide, and Rodenticide Act.
- Historical and Archaeological Preservation
    - Section 106 of the National Historic Preservation Act
    - Section 110 the National Historic Preservation Act
    - Archaeological and Historic Preservation Act
    - Archaeological Resources Protection Act
    - American Indian Religious Freedom Act
    - Native American Grave Protection and Repatriation Act.
- Land and Water Usage
    - Wilderness Act
    - Wild and Scenic Rivers Act
    - Land and Water Conservation Fund Act
    - Executive Order 11990: Protection of Wetlands
    - ISTEA: Wetlands mitigation, banks, recycled pavement materials, and scenic byways
    - Emergency Wetlands Resources Act of 1986
    - National Trails Systems Act
    - National Recreational Trails Fund Act of ISTEA
    - Rivers and Harbors Act of 1999
    - Federal Water Pollution Control Act (1972)
    - Executive Order 11988: Floodplain Management
    - National Flood Insurance Act
    - Marine Protection Research and Sanctuaries Act of 1972
    - Water Bank Act
    - Coastal Zone Management Act of 1972
    - Coastal Barriers Resources Act
    - Great Lakes Coastal Barriers Act of 1988
    - Farmland Protection Policy Act of 1981
    - Resource Conservation and Recovery Act of 1976 (RCRA)
    - Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA)
    - Endangered Species Act of 1973
    - Fish and Wildlife Coordination Act
    - Migratory Bird Treaty Act.
- Noise
    - Noise Standards, 23 USC 109.
- Air
    - Clean Air Act Transportation Conformity Rule and Clean Air Act Sanctions
    - ISTEA (1991) Congestion Mitigation and Air Quality Improvement Program.

The regulatory process can have a profound impact on transportation projects, especially those administered by local agencies with small staffs that frequently lack the ex-

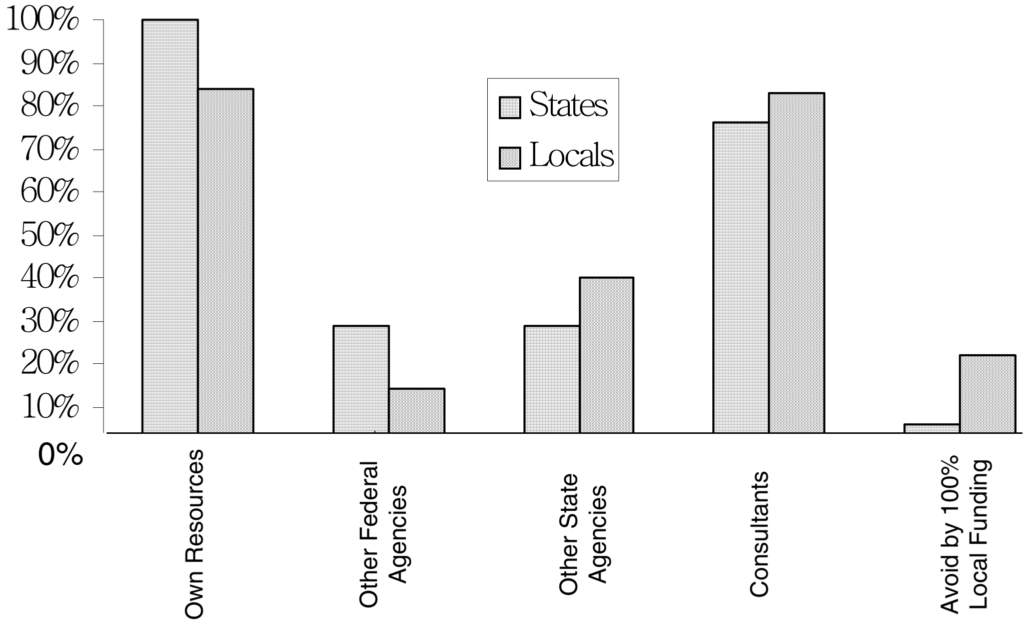


FIGURE 18 Agency responses concerning environmental process coordination.

pertise required to navigate the environmental permitting process. It was of interest to gain insight into the process and problems of interagency cooperation.

For projects that require interagency coordination, permitting, etc., the survey attempted to determine what resources were employed. The combined responses of state and local agencies are presented in Figure 18, which depicts the percentage of agencies that have used the various resources, not the frequency of which they are used.

As expected, most state and local agencies use some of their own resources to coordinate with other government agencies to proceed through the permitting process. However, approximately one-sixth of the local agency respondents do not use their own employees for such work. Also of interest is that local and state agencies indicated that a means of circumventing the coordination process is to use 100% local funds. Approximately one-third of state and local agencies indicated that this process is occasionally used.

Various suggestions concerning the environmental documentation and permitting process were presented. These suggestions included the use of simplified checklists for permit applications, increased consistency among federal and state requirements and among various federal agencies with differing requirements, and more rapid processing of permit requests. There appears to be confusion among some agencies as to what the process actually entails, that is, what steps and in what order. These comments were presented in the context of archaeology and wetlands investigations. Several comments concerning the permitting process emphasized the need for more lenient criteria for minor impacts, especially those in "low quality" environmental areas. The perception is that the permit process should be tiered and tailored to the quality of the local environment. To paraphrase one of the responses, "Regulations intended to protect pristine wetlands may be inappropriate for low quality environments or marginal impacts." It was suggested that the environmental process be greatly simplified for bridges replaced in kind or with improvements to hydraulic capacity. A similar comment was presented concerning bridge replacements on the same line and grade as the existing structure. One state agency commented that increased project costs directly attributable to the regulatory actions of another agency should be borne by the agency requiring the expense. Another comment was that the cost of regulatory compliance has a significant impact on the total budget available for construction.

One of the tools that both local and state agencies may find particularly useful in navigating the various permitting requirements is a series of environmental flowcharts developed by the FHWA for use in the environmental process, which can be found in the *Environmental Guidebook*. Examples of two of the flowcharts for the NEPA and Section 4(f) processes are depicted in Figures 19 and 20.

Although there are numerous pieces of environmental legislation cited in the bulleted list, many of these statutes

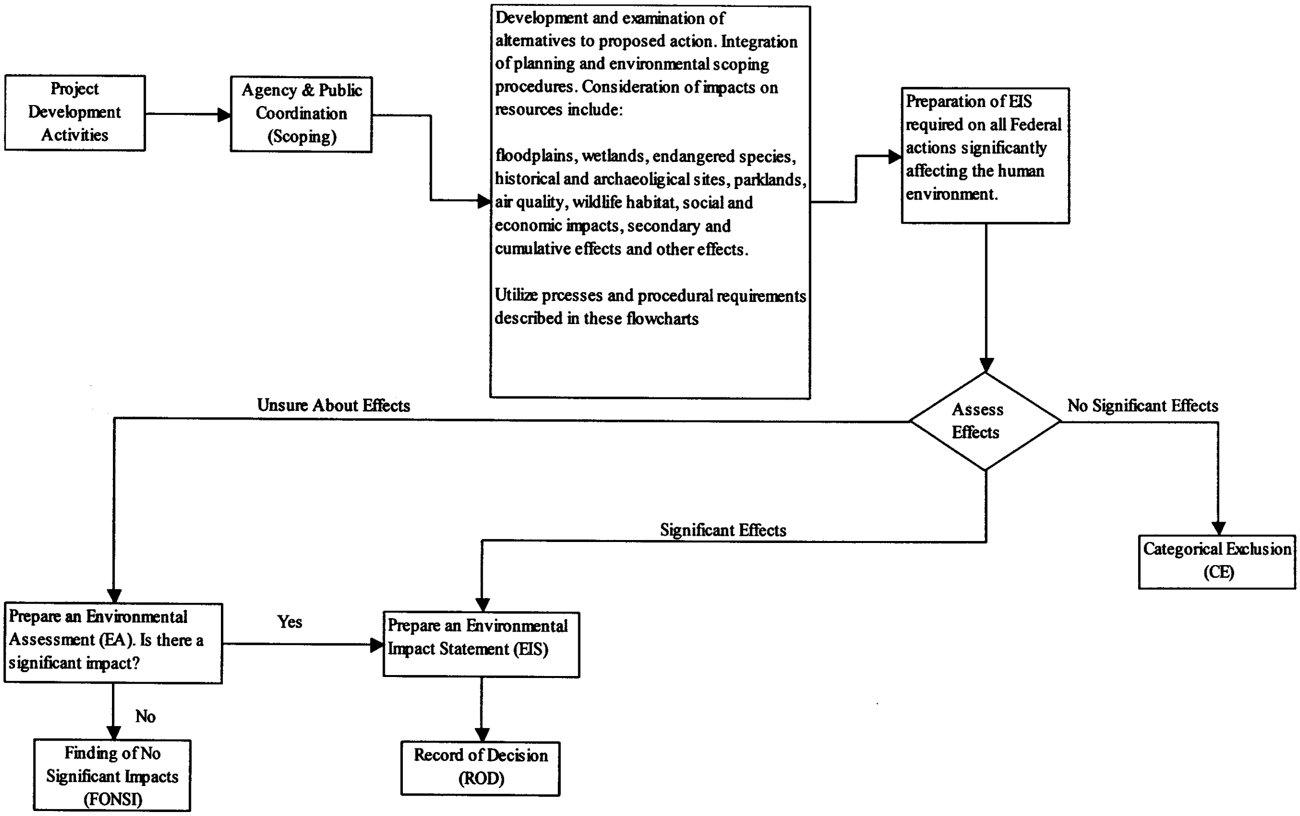


FIGURE 19 NEPA process flowchart from FHWA *Environmental Guidebook* (1999).

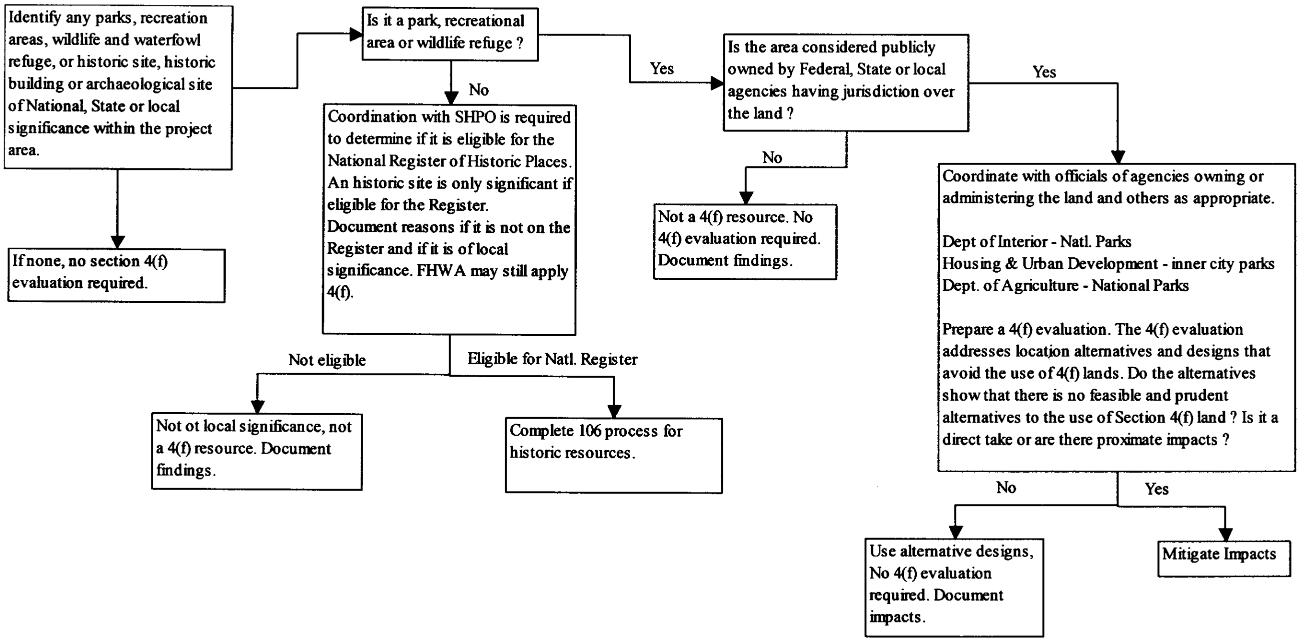


FIGURE 20 Section 4(f) process flowchart from FHWA *Environmental Guidebook* (1999).

are infrequently encountered. The following text focuses on several of the more frequently encountered and substantive regulations. The lack of a citation does not imply that a particular statute is not important; it is only a consideration of space and the focus of this report.

National Environmental Policy Act

As previously mentioned, the National Environmental Policy Act of 1969 (NEPA) process was established to require the consideration of all general environmental factors in the process of highway (and hence bridge) planning, rehabilitation, reconstruction, replacement, or new construction. It is applicable to any and all projects in which federal money is involved. This includes projects where the funds administered are grants made to the states for their redistribution to local agencies.

Section 4(f)

The Section 4(f) legislation refers to Section 4(f) of the Department of Transportation Act and is intended to protect public resources as well as historical and archaeologically significant sites from "use" in a transportation project. In general, the statute is employed to ensure that all feasible and prudent alternatives to the use of the protected site have been considered. Section 4(f) is one of the most substantive environmental processes. It has the authority to halt projects for which the environmental consultation and study process is deemed to be insufficient.

Historic Bridges

Historic bridges are one of the most challenging aspects of bridge rehabilitation and replacement. Bridges regarded as historic are specifically protected based on their listing or listing eligibility on the National Register of Historic Places. They are protected by various pieces of legislation including the Department of Transportation Act of 1966, Federal-Aid Highway Act of 1968, NEPA (1969), National Historic Preservation Act (NHPA) of 1966 (Section 106), the Surface Transportation and Uniform Relocation Act of 1987, and more recently the ISTEA and TEA-21 legislation. ISTEA and TEA-21 have incrementally added to the legislative strength of historic bridge protection while also mandating increased upgrading of the deficient highway infrastructure.

The NHPA was enacted in 1966 and includes the requirements in Section 106 for the protection of historic properties that might be affected by federal undertakings (or undertakings indirectly using federal funds). A consultation was required if an undertaking was to affect an eligible or potentially eligible property (including bridges to be demolished or substantively modified) and this consultation was generally to involve the Advisory Council on Historic Preservation and the State Historic Preservation Office. This consultation and the Section 106 process are not substantive in that there is no guaranteed protection, only a requirement that a consultation take place. If following the consultation mitigative actions are deemed punitive or overly burdensome, nothing else is required of the agency proposing the undertaking.

The Department of Transportation Act of 1966 was the first modern legislation that required the determination of the impact of a project on historic properties if federal funds were to be used. The Department of Transportation Act was similar in language to the NHPA, but had a substantive component that could restrict action. These provisions are commonly referred to as the 4(f) provisions. In the simplest sense, the 4(f) requirements are such that all "feasible and prudent alternatives" must have been explored before "use" of the historic property is permitted. Alternately, all planning must have been done in a fashion so as to minimize harm to the protected feature. For historic bridges in poor condition these requirements are substantial. It must be shown that there are no "feasible and prudent" alternatives to significant alteration or demolition and that even in the case of retention, all measures to minimize harm have been explored. For deficient bridges with inadequate safety features, insufficient capacity, and other common problems of old bridges, the planning and study required to satisfy the 4(f) provisions is significant. The 4(f) requirements are also more far reaching than those of the Section 106 process because they also encompass properties that are not National Register eligible but that are simply locally significant or are contributing elements to a greater historic district.

The requirements set forth in the various pieces of legislation are both significant and restrictive. Preservation is clearly a national goal and is on par with highway safety, and these two issues must be evaluated concurrently. The problem that many bridge owners have in interacting with the legislation involves how to balance the choices for preservation with highway safety. Some flexibility is provided in the "feasible and prudent" criteria. Many choices are available that are "feasible" as it relates to the "use" of significant resources; however, the list of "prudent" options may be a much shorter list or nonexistent. There is always the "do-nothing" option, which solves no problems. With the do nothing alternative, a protected resource will continue to deteriorate, an equally unappealing option. Eilers and Vedder (1996) advocated amendment of the 4(f) requirements to exclude bridge projects initiated by the unsafe nature of a structure. The only requirements advocated are the consultative ones required in the Section 106 process. Eilers and Vedder asserted that a choice must be made between preservation and safety and that safety is the more appropriate goal.

The options available for historic bridges generally involve rehabilitation at the current site, replacement, and adaptive reuse. Even rehabilitation for continued use at the same location must be carried out in a manner consistent with respect for the characteristics that make a structure historic or significant. Incompatible work should be avoided wherever possible.

Replacement is typically only permitted once the feasible and prudent criteria have been evaluated with respect to rehabilitation and found noncompelling. Even in the case of replacement, the bridge must be made available to another owner provided its historic character is maintained [23 USC 144 (o)]. Doing so is typically costly, because it requires relocation of the bridge. Additionally, the accepting party must agree to undertake the upkeep of the bridge to keep its historic integrity and eligibility. These costs, relocation, and upkeep may be prohibitive for the agencies likely to have interest in such preservation.

The final option is adaptive reuse, which involves conversion of the highway bridge to another function. In the case of roadway relocation, the existing bridge could be preserved on its existing alignment as a trail. The bridge could also be relocated to a park to serve as a stream crossing, monument, or other use that allows for its continued use as a bridge but in an alternate way.

To navigate the process of historic bridge preservation, rehabilitation, and replacement, a number of states have developed guidelines and manuals for the treatment of historic bridges. These states include Texas (*Historic Bridge Manual* 2001), Virginia (Miller et al. 2001b), and Oregon among others. A search of DOT websites revealed many states with either specific historic bridge management plans or portions of a design manual with discussions of the historic bridge process for their state. Additionally, NCHRP has previously funded work in this area. These studies include Chamberlin (1983, 1999).

Miller et al. (2001b) provided significant background information into the historic bridge process from both a national perspective and with specific reference to the development of a management plan for historic bridges in Virginia. Funding problems, design criteria, liability, and other issues are explored.

Because of the vast network of historic and potentially historic bridges in Virginia, a comprehensive management plan was needed that would both identify the significant structures, properly plan for their future use and disposition, and expedite the environmental process as each bridge is "used" in the future. Each historic bridge in the state under control of the Virginia DOT now has a specifically developed management plan. The Virginia DOT study identified the following issues as critical for developing a comprehensive historic bridge management plan:

- Treatment options;
- Use of the *Secretary of the Interior's Standards*;
- Current and potential funding sources;
- Liability and safety issues;
- Right-of-way constraints;
- Present and future use;
- Interagency cooperation and dispute resolution;
- History of data gathering;
- Explanation of significance;
- Bridge decision matrix—that is, weight of each sufficiency factor;
- Vulnerability to natural disaster;
- Citizen interests;
- Political implications;
- Emergency procedures; and
- Design standards.

Suggestions and discussion related to these issues are presented in Miller et al. (2001b), which is available on-line.

River, Stream, and Wetland Protection

Activities involving potential impacts to natural resources are among the most regulated and frequently encountered in transportation projects, specifically road and bridge construction. As shown in the list from *Summary of Environmental Legislation Affecting Transportation*, on page 98, the greatest amount of regulation is with respect to Land and Water Usage. These regulations, and the additional 4(f) mandates to evaluate all feasible and prudent alternatives, are substantive requirements. Whereas 4(f) requires a study process but not specific outcomes, the various executive orders and federal, state, and local legislation do have the ability to prohibit, by means of denial of funds or permits, specific construction and alterations to the environment. Among the most frequently encountered challenges are those related to wetlands and stream or river intrusions.

Among the regulations encountered relative to wetlands and river and stream intrusions is the Clean Water Act, specifically the provisions of Section 404. Section 404 is intended to control the discharge of dredged or fill materials into any portion of the waters of the United States, including wetlands. Section 404 expressly prohibits construction that requires fill or dredged material to be discharged into an area that is considered the waters of the United States, unless it can be shown that no other practicable alternative exists or that the discharge has a negligible impact. Some activities, such as emergency reconstruction or maintenance of bridge structures, are exempt from obtaining 404 permits, but any use that was not pre-existing must be evaluated and permitted.

There are several mechanisms for permitting under the 404 process. The requirements for permits are delineated in 33 CFR 322, *Permits for Structures or Work in or Affecting Navigable Waters of the United States*. The most general permit is an individual permit, which requires application to the USACE for specific construction activities at a site. However, to avoid individual permit applications for common activities, broader general or nationwide permits are used. The nationwide permit process is defined by 33 CFR 330, *Nationwide Permit Program*. Additional regional permits can be issued that exempt categories of work from individual permits, but only in specific regions of the country. Agencies are encouraged to explore the option of construction under the nationwide or regional permit authority in lieu of proceeding with individual permit applications.

There exists a nationwide permit for bridges, permit 14—*Linear Transportation Crossings*. This permit allows for the use of wetlands and encroachment into tidal or nontidal waters provided that impacts to the waters of the United States are less than a *de minimus* amount; this amount is dependent on the type of feature crossed. The nationwide permit is intended to be used on a bridge-by-bridge basis and not to authorize multiple crossings of the same stream. Multiple crossings are subject to permitting on an individual permit basis. Additionally, there are restrictions to the use of nationwide or regional permits if associated impacts are present, such as the potential impact to historic properties, endangered species, wild and scenic rivers, and other protected classes of resources. Construction under a nationwide permit requires implementation of erosion and sedimentation controls as does construction using individual permits.

An additional regulation regarding the pollution of waters of the United States by the effects of construction is the National Pollutant Discharge Elimination System (NPDES) provision of the Clean Water Act ("Storm Water Discharges. . . ." 2001). The NPDES program specifically regulates storm water discharge from construction activities. The types of construction typically found in the rehabilitation of off-system bridges would be covered in Phase II of the NPDES provisions (*Storm Water Phase II . . .* 2000). Phase II specifically addresses pollution control requirements and measures for small construction activities on sites of 1 to 5 acres. Even sites of less than 1 acre may be subjected to the NPDES process if so designated by the permitting authority.

The environmental process is complex and has only been partially described in the previous text. The intent was to highlight some of the challenges and mandates relative to coordination and navigation through the study and permitting process. Environmental documentation can be time consuming and expensive and becomes more so when improper planning occurs. There are numerous pitfalls and potential roadblocks if the planning phase of the project is not performed in the proper sequence and with sufficient time for various agencies to review and comment. Local agencies are encouraged to maintain active relationships with permitting agencies, avail themselves of the many electronic resources regarding environmental compliance (EPA and USACE websites to name a few), and look for innovative ways to maintain and construct new structures so that impacts are minimal and require the least amount of review and oversight. Consideration should be given to the selection of structure types that minimize intrusions into streams; employ active management, maintenance, and planning relative to historic structures; and employ construction procedures that promote the quality of the natural resources. These points were explored in the preceding text. It must be stressed that close cooperation among local, state, and federal agencies is imperative for the process to run as smooth as possible, given that there will certainly be disagreements and changes as a project progresses.

INTERAGENCY COOPERATION AND PARTNERING

A statistical analysis of structurally deficient and functionally obsolete rural bridges was conducted with the objective of determining what factors relative to government policies, state demographics, and funding mechanisms were strongly correlated to rural bridge conditions (Nice 1992). Using bridge condition data from the late 1980s and early 1990s it was shown that rural bridges on the federal-aid system carry approximately 90% of rural bridge traffic, but make up only 41% of rural bridges. The large number of rural bridges not on the federal-aid system, although carrying only 10% of the rural traffic, is subject to the funding availability of state and local governments.

The study found that federal aid is associated with "sounder" bridges and states with heavy reliance on local funding, by virtue of few federal-aid bridges, tend to have more bridge problems. The author points to several reasons for a higher percentage of bridge problems on local roads, including inadequate funds and a disparity of funds from locale to locale. However, additional considerations include the sometime limited experience of local government officials in the administration of transportation infrastructure and the lack of attention, maintenance, and monitoring that may result. States with a large number of bridges relative to population, and with primarily rural populations, have greater difficulties in maintaining the quality of their bridges. The competition for funds for many poor bridges, most with small traffic demands, can be a difficult problem when the funding is primarily local.

The study also found that federal support and guidelines help promote higher overall quality and uniformity. The percentage of Federal-Aid Highway bridges that are deficient or obsolete is less than that for non-Federal-Aid Highway bridges in most states. The author contends that some of the trends are strictly related because federal-aid bridges carry higher traffic volumes and therefore would be expected to receive greater funds. Also, Federal-Aid Highway bridges are still deficient or obsolete in large numbers; therefore, the existence of federal funds is not by itself a guarantee of high quality. However, the conclusion is somewhat evident; bridges in rural areas under local control are more likely to have structural or functional problems. Coupled with limited funds, a real need for efficient management of the existing bridge population exists

A report by the National Academy of Public Administration (NAPA) (*Rural Transportation Consultation Processes* 2000) discusses the effectiveness of the participation of local officials in nonmetropolitan areas in transportation planning and programming. The report was required as a component of the TEA-21 authorization process. The study has its origins in the dissatisfaction of some local officials with respect to their level of input in the state transportation planning and programming processes.

There are two levels of coordination required between state and local agencies on federally funded projects, consultation and cooperation. Consultation requires that the state consider a local agency's position, but is under no obligation with respect to apportionment of funds. However, for federal funds used on non-NHS projects, decisions are to be made in cooperation with local agencies [23 USC 135(f)(3)]. An exception to these criteria is for bridge and interstate maintenance programs, where the requirement is for consultation only. Outside of the jurisdictions of metropolitan planning organizations there are no standard methods for interacting with local agencies relative to programming transportation needs. In addition to the lack of a formal partnering process, another major change brought forth with the ISTEA and TEA-21 legislation was the dissolution of the Federal-Aid Secondary System and the dedicated funding that accompanied it. Replaced for the most part by the more flexible Surface Transportation Program, the new system has a broader range of projects for which its funds can be used. The disbanded Secondary Roads program, once a powerful vehicle for interaction between the states and rural locals, has been replaced in some states with "state secondary" programs. Enhanced collaboration is now seen as an important issue for rural road owners.

To judge the effectiveness of the consultation process, NAPA met with the FHWA, held a special workshop, met a number of times as a panel, and conducted a literature review. The findings from the NAPA study are as follows:

- Consultations with local officials are crucial to making transportation delivery systems work well in the states.
- Consultations can be most useful to all the parties if they are conducted using a framework of dialogues about planning, programming, and results.
- States have many different characteristics—geographically, economically, demographically, governmentally, and in the nature of their transportation systems and decision-making processes, that need to be taken into account when state DOTs design their consultation processes.
- Many different state–local consultation practices exist and are being used by state DOTs.
- No single practice or set of practices will meet the consultation needs of all states.
- From various fields of research and experience there are long-established principles of effective consultation that can be used to improve consultation processes in transportation planning and programming over time.
- There are several ways the principles of effective consultation can be used to improve the state–local consultation practices and processes of state DOTs.
- Additional work would be needed to assess the effectiveness of state DOT consultations with nonmetropolitan local officials in each state.

CHAPTER SIX

CONCLUSIONS

This synthesis has explored various aspects of off-system and local interest bridge design, construction, maintenance, rehabilitation, and replacement. Information was gathered from various sources, including a project survey, published literature, electronic media, personal contacts, and bridge product manufacturers. The report also identified areas where improvements need to be made in the current practice, including design standards, maintenance, rehabilitation, and replacement strategies. The major findings from this study are presented here.

Only a small percentage of the several hundred surveys disseminated electronically to state and local agencies throughout the United States were returned. Responses were received from 20 state and 70 local agencies, with many of the local agency responses coming from a small group of states. The survey results indicated general agreement between state and local agency respondents on many issues.

The concrete box culvert is the most preferred bridge type for new construction, a reflection of its ease of design, construction, and maintenance. It also correlates well with the statistic that approximately 80% of the bridges in the National Bridge Inventory (NBI) database are over water, the usual application for culverts. In addition, concrete box culverts were ranked as the most maintenance free. First cost was determined to be the most important criteria when selecting a new bridge.

Typically, consulting engineers and outside contractors are used for the design and construction of off-system bridges. The survey respondents indicated that the use of in-house resources is more cost-effective; however, either limited resources and staff or legislative restrictions on work that can be done with in-house staff can restrict their ability to take advantage of these economic benefits.

Numerous survey responses reported on the need for flexible design standards for low-volume/off-system bridges, for relaxed permitting requirements, and for more flexibility in project funding. Several respondents mentioned the need for additional pre-engineered standard plans. The responses indicated a general concern for legal liability in exercising flexibility relative to the application of structural and geometric design criteria.

In 2000, NBI data indicated that there were approximately 587,000 bridges in excess of 6.1 m (20 ft) long. There are also a large number of bridges less than 6.1 m (20 ft) long; however, information on their number, condition, and ownership are not as readily available. Of the bridges for which data are available, the picture is one of extensive deterioration and deficiencies, with a large number of the deficient bridges on locally owned or other low-volume roads. More than 100,000 NBI-catalogued bridges qualify for replacement and more than twice that number are eligible for federal Highway Bridge Replacement and Rehabilitation Program (HBRRP) matching rehabilitation funds. Approximately 30% of the NBI bridges are considered structurally deficient or functionally obsolete. Approximately 1 in 6 bridges have intolerable deck geometries and 1 in 10 have intolerable structural condition appraisals. Routine maintenance, which may have prevented some of the more pervasive deterioration problems, is not eligible for federal funding. However, recent changes in the HBRRP program have clarified the federal position; HBRRP funds may be used for preventative maintenance activities that are demonstrated to extend the useful life of a bridge.

Appropriation of funding should be done with careful planning and systematic evaluation of needs. Better decisions need to be made in all of the areas of bridge maintenance, rehabilitation, and replacement. These choices could involve more “data-based” decision making, such as those made possible through asset/bridge management and through the use of maintenance, rehabilitation, and replacement construction techniques and materials that promote long life and minimal maintenance. Significant research is ongoing to develop improved materials, such as high-performance concrete and steel, as well as fiber-reinforced polymer products. These materials could make a valuable contribution to the off-system bridge network in addition to the more high-traffic networks where their use is advocated. The benefit to the off-system network comes from their ability to function as “build and forget” solutions, because these materials all have the promise of long life, excellent durability, and minimal maintenance.

Various administrative challenges pertaining to the management of diverse off-system bridge populations were explored. These administrative issues are summarized in the following paragraphs.

This synthesis emphasized the importance of administrative tools, such as bridge and asset management (and bridge management systems) for off-system bridges, especially in light of the aforementioned budgetary pressures and funding shortfalls. Only through systematic inspection and proper programming can the current funding mechanisms be most efficiently used. However, it must be emphasized that many bridge and asset management systems rely on historic cost data and these data may not be readily available for many small agencies. However, bridge and asset management should be employed to the degree possible consistent with the technology and data constraints of each individual agency.

A discussion was presented on the various sources of funding (and potential sources for new funding) for off-system bridges. The sources included traditional forms such as the HBRRP federal funds, but with additional explanation of the flexible soft match provision that some local agencies are using to advance their own rehabilitation needs. Additional federal funding sources include the Surface Transportation Program and the Innovative Bridge Research and Construction Program. Both of these programs are minor sources of funding for bridge construction, although the Innovative Bridge Research and Construction Program has the potential to significantly improve future bridge construction.

To address the difficulties of the project environmental process, and acknowledging that some local agencies might not be completely cognizant of the process, this synthesis provides brief descriptions of some of the more substantive environmental processes likely to be encountered on a routine basis. The National Environmental Policy Act process is described, as well as some of the environmental requirements of the 4(f), Section 106, Clean Water, and Wetlands requirements. This information is by no means a complete treatment of the transportation project environmental process; however, references are provided where local bridge owners can obtain assistance.

It was learned from the survey that both state and local agencies consider bridge decks to be their most significant maintenance problem; approximately one-quarter of the two groups ranked them as their most pressing concern. Consistent with this concern, many of the maintenance techniques cited are those aimed at prolonging the life of bridge decks. Various maintenance and rehabilitation techniques are provided in the survey results.

The majority of those responding to the survey (approximately 85% of each group) use the traditional AASHTO *Manual for Condition Evaluation* to rate existing bridges. A limited number (18% of the states and 15% of the local agencies) use load testing to rate bridges.

Along with comprehensive information on bridge rehabilitation and repair, a similar significant discussion is presented on various aspects of bridge replacement. This includes a survey of previous work, a review of the project survey results, and an in-depth discussion of various options for off-system bridge replacement. Additionally, recognizing that engineering design can represent a substantial cost for many bridge owners, sources of available pre-engineered bridges are provided. Additional information is presented on bridge design aids and bridge design software, all of which are intended to expedite the bridge replacement engineering process.

This synthesis has identified many existing deficiencies and also many repair, rehabilitation, and replacement options that off-system bridge owners can employ. These choices are not universal and are likely to have varying degrees of cost-effectiveness and success in different regions of the county. However, this synthesis can be considered to be somewhat of a "user's manual" or "toolbox" of information and choices for off-system bridge owners. It cannot solve some of the underlying problems relative to interagency coordination, funding problems, and the length and complexity of the permitting process, but it does highlight the problems so that interested parties are aware of the challenges.

AASHTO has taken the first step concerning the need for adjusted design standards for off-system bridges with their recent publication of a geometric design guide for low-volume roads. It has been suggested by some researchers, and is discussed herein, that a similar modification is appropriate for structural design. This synthesis located several studies that concluded that some structural design criteria such as deflection and fatigue might be relaxed or disregarded entirely for off-system bridges. However, there is also evidence of increasing truck weights throughout the nation that counters the desire for relaxed design criteria. Some valid arguments for lower design loads (e.g., considering a single lane of heavy trucks on narrow bridges) can be made; however, there is insufficient evidence to support the adoption of a lower structural design standard at this time. In contrast, a study of designs at the standard MS 18 (HS 20) design level compared with MS 13.5 (HS 15) designs by the Concrete Reinforcing Steel Institute revealed a material savings of only a few percent and results in a bridge likely to be posted or in need of repairs earlier than one designed for the default design loads.

In terms of structural criteria likely to have a significant effect on bridge costs, the issue of railing design should be considered more carefully on off-system bridges. Previously, the user had the choice of railing systems that were either not crash tested (and thus unproven) or standard relatively expensive reinforced concrete railing options. Owing primarily to the research conduced by the timber industry and the FHWA/U.S. Department of Agriculture Forest Products Laboratory, a series of less expensive timber and steel bridge railings have been developed for use with either timber or concrete bridge decks. Additionally, several states have developed state standard railings for use on off-system bridges. These railings are safe, as they are now mandated to be crash-tested, and are likely to represent a cost-effective solution for off-system bridges.

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APPENDIX A

Project Questionnaire and Responses

A key component of the process for this NCHRP Synthesis was the collection of information from industry members, traditionally bridge owners. For this project, a questionnaire was developed and circulated to various potential respondents including state departments of transportation (DOTs), county and local bridge owners, and consultants involved with off-system bridge design and rehabilitation. The assistance of the National Association of County Engineers and TRB staff was employed to disseminate the survey to all potentially interested parties. In all, several hundred surveys were distributed electronically by means of e-mail.

Owing to the scope of this synthesis, a general study of off-system bridge issues, the questionnaire was broader based and intended to acquire more general information than questionnaires developed for more specific synthesis topics. Because of the broad nature of the questionnaire, the depth of inquiry in any one particular area of interest was limited in the hopes of gathering pertinent information with a questionnaire length consistent with an expected high response rate. Specific areas of inquiry were

- General Information (number of bridges and conditions),
- Structure Design Criteria (for new bridges),
- Highway Design Criteria (for new bridges),
- Bridge Types (for new bridges),
- Maintenance (policies),
- Maintenance and Rehabilitation Options,
- Design Criteria and Funding, and
- Regulatory Agencies (coordination with oversight and permitting agencies).

The following summary of survey responses is representative of the information provided by state DOTs and local agencies regarding their policies for off-system bridges. In addition to the brief summaries provided here and in chapter one of this report, specific references to certain portions of the survey are found throughout the body of the report.

In many cases the questions requested that the user choose from various options whose sum should equal 100% in total. However, a number of the surveys are incomplete, and therefore the results do not necessarily sum to 100%. Additionally, several questions, for example, BT-11, request information about various forms of construction in use. Because agencies may use all or at least some of these items, a response indicates use only, not what percentage (or ranking) of each type of construction is performed.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Project 20-5

Synthesis of Highway Practice 32-08

"Cost-Effective Structures for Off-System Bridges"

Owner Survey

The following is the scope of the aforementioned project. In the spirit of collecting the most accurate and useful information for this important study, please be as complete as possible in answering the following survey. If you feel there is a more appropriate or additional person to respond to this survey, please forward it for their consideration. Although there are some generic questions, the vast majority of the questions in the enclosed survey should be answered as they relate to "off-system" structures in your jurisdiction. By "off-system" the study team is referring to bridges not on the NHS [National Highway System]. Your time and efforts are valued and form a strong base of information for this synthesis.

There is a nationwide need to encourage counties and cities to improve the overall sufficiency rating of their structure population. A synthesis of the existing practices and processes used to satisfy reasonable operating standards for off-system bridges and approach roadways is needed.

Bridges that are relatively inexpensive to design, build, and maintain, and that are capable of safely carrying oversized equipment, frequent loading by school buses, and infrequent over-loading by heavy commercial trucks are of particular interest. This may result in the replacement, repair, and/or rehabilitation of substandard bridges and thus increase the efficiency and safety to the traveling public.

The synthesis will survey state departments of transportation (DOTs), local agencies, and the literature to document the practices that lead to the most economical, safe, and functional off-system bridges. These bridges are defined as those under local jurisdiction.

Specific items of interest include, but are not limited to

- Structural design criteria (e.g., design loading, deflection, fatigue, and scour),
- Geometrics (e.g., width, height, and alignment),
- Bridge railing (e.g., at the appropriate crash test level),
- Construction practices (e.g., local agency forces vs. contract, delivery of materials, and constructability),
- Compliance with environmental regulations (e.g., permitting),
- Teamwork (e.g., local, state, and federal partnering),
- Initial cost and maintainability,
- Funding (e.g., resources available to state and local agencies), and
- Stockpiling of bridge components (e.g., precast/prefabricated elements, recycled and new elements).

The information you provide will be valuable input to the development of a synthesis of "Cost-Effective Structures for Off-System Bridges."

Please return your completed questionnaire, along with any supporting documentation, by __________to:

Terry J. Wipf
Manager, Bridge Engineering Center
Dept. of Civil and Construction Engineering
Iowa State University
Ames, Iowa 50011

If you have any questions about the survey, please contact Prof. Wipf (Phone: 515-294-6979; Fax: 515-294-7424; E-mail: wipf@iastate.edu), Prof. F. Wayne Klaiber (Phone: 515-294-8763; Fax: 515-294-7424; E-mail: klaiber@iastate.edu), or Dr. Frank M. Russo (Phone: 610-337-3666; Fax: 610-337-2149; E-mail: frank_russo@urscorp.com).

GENERAL INFORMATION

Using the definition for off-system bridges described in the cover sheet of this questionnaire:

GI-1. How many bridges do you have in this category?

States:	6,562 (average number of off-system bridges per state)
Locals:	136 (average number of off-system bridges per local agency)

GI-2. What percentage of your total bridge population does this number represent?

States:	58%
Locals:	85%

GI-3. What percentage of this number carry a sufficiency rating?

less than 80?	States:	40%	Locals:	45%
less than 50?	States:	14%	Locals:	19%

GI-4. Besides the Sufficiency Rating, what other factors are considered when establishing bridge work priorities?

- State Agency Responses—Coordination with other projects; available funds; safety; scour effects; essentiality; community impact of temporary or permanent closure; load capacity; roadway width; detour length; current maintenance expenses; off-system bridges are prioritized by those rated less than 10 tons; future regional development; accident history.
- Local Agency Responses—Cost vs. traffic volume; route type (snow emergency, high priority, etc.); ability to use in-house vs. contract forces; emergency service and school bus access; matching fund availability; detour length; bridge joint condition; expected fatigue life; political pressures and local land use changes; road improvements that dictate changes in bridges; impact on local businesses.

STRUCTURE DESIGN CRITERIA

SD-1. Do you use bridge design criteria other than the AASHTO *Standard Specifications for Highway Bridges*?

States:	33%	Yes	67%	No
Locals:	19%	Yes	68%	No

What if any changes to this design criteria have you made regarding

Loads Value: ___________________
Allowable Deflections Value: ___________________
Fatigue/Cyclic Loading Value: ___________________

SD-2. Do you have a published design exception criteria for bridges? If yes, please provide a copy of them.

States:	29%	Yes	71%	No
Locals:	6%	Yes	81%	No

SD-3. How do you determine if a bridge requires posting? If a bridge is posted, what types of vehicle(s) are used to determine the bridge posting?

- Combined Response—Bridge posting is generally determined by use of computed inventory and operating ratings; some states or local agencies post based on inventory rating, others based on the operating rating. The standard AASHTO rating vehicles including the HS, H, Type 3, 3S2, and 3-3 vehicles are all cited. Additionally, some respondents have agency specific vehicles and minimum legal loads.

HIGHWAY DESIGN CRITERIA

HD-1. Do you use highway design criteria other than that presented by AASHTO's *Policy on Geometric Design of Highways and Streets*?

States: 44% Yes 56% No
Locals: 23% Yes 70% No

- Combined response—West Virginia indicated use of design criteria on rural roads less than that recommended by AASHTO that results in many of their bridges being automatically classified as functionally obsolete. State respondents provided no other substantive comments. County respondents from Maryland, New York, and Illinois indicated use of roadway policies specifically implemented for local roads and low-volume bridges.

HD-2. Do you have a published design exception criteria for highways? If yes, please provide a copy of it.

States: 47% Yes 53% No
Locals: 9% Yes 83% No

- Only a few respondents indicated in any detail what their design exception criteria were. No copies were provided for review.

BRIDGE TYPES

BT-1. All things being considered equal with regards to geometrics do you favor one type of construction over another? Please rate in order of preference (1 being your first choice); indicate equals by using the same number.

States, Locals:

19%,	15%	Structural Steel (rolled shapes, plate girders, truss, etc.)
15%,	17%	Reinforced Concrete (T-beams, slab bridges, etc.)
21%,	20%	Concrete Box Culverts (precast and CIP)
13%,	16%	Structural Pipe/Steel Arch Culverts
22%,	19%	Prestressed Concrete (I-beams, boxes, slabs, etc.)
9%,	12%	Timber (glulam and sawn beams, glulam deck bridges, etc.)
1%,	2%	Other (specify, e.g., proprietary system)

BT-2. For the same types of construction listed above, would you expect to use your own labor force and equipment or let a contract for construction?

State Responses:

13% Own	87% Con	Structural Steel (rolled shapes, plate girders, truss, etc.)
7% Own	93% Con	Reinforced Concrete (T-beams, slab bridges, etc.)
25% Own	75% Con	Concrete Box Culverts (precast and CIP)
25% Own	75% Con	Structural Pipe/Steel Arch Culverts
13% Own	87% Con	Prestressed Concrete (I-beams, boxes, slabs, etc.)
33% Own	67% Con	Timber (glulam and sawn beams, glulam deck bridges, etc.)

Other ____

Local Responses:

19% Own	74% Con	Structural Steel (rolled shapes, plate girders, truss, etc.)
14% Own	81% Con	Reinforced Concrete (T-beams, slab bridges, etc.)
23% Own	73% Con	Concrete Box Culverts (precast and CIP)
43% Own	51% Con	Structural Pipe/Steel Arch Culverts
9% Own	83% Con	Prestressed Concrete (I-beams, boxes, slabs, etc.)
37% Own	53% Con	Timber (glulam and sawn beams, glulam deck bridges, etc.)

Other ____

BT-3. In an effort to obtain information on the use of pre-engineered or prefabricated components in off-system bridge rehabilitation and replacements, please provide the names of prefabricated bridge/culvert products you have used in the past.

- Precast Concrete Products (Standard ASTM Culverts, Bebo, ConSpan, HySpan). In addition to proprietary products, various uses of standard precast concrete beams and slabs. Also documented use of owner fabricated precast concrete sections for short to medium spans.
- Prefabricated Steel Structures (prefabricated trusses, i.e., U.S. Bridge, Acrow Panel, Continental Bridge, Mabey Bridge, Bailey Bridge; steel and aluminum pipe arches; Inverset bridges).
- Timber Structures (timber beams, timber decks on timber beams, timber decks on steel beams, nail laminated panels, glulam pier caps, and bridge rails).
- Others (steel and aluminum grid decks, exodermic decks, HDPE pipe culvert).

BT-4. In instances where you have used prefabricated or pre-engineered components to rehabilitate or replace a portion of a bridge or a bridge in its entirety, rank the following criteria in terms of importance (percentages indicate order of importance).

States, Locals:

20%,	23%	Total cost
21%,	17%	Speed of construction
20%,	18%	Traffic considerations
12%,	21%	Lack of engineering staff
17%,	12%	Anticipated durability
10%,	9%	Lack of other options

BT-5. Please list any commercial design software and/or standard plans you have successfully used for the design of off-system bridges.

- Software Programs
  - Concrete structures—LEAP software, PCA SLABBRDG, PennDOT PSLRFD Software.
  - Steel structures—AISI Short Span Steel Bridge Plans and Software, MDX, Brass Girder, Merlin Dash, Georgia Beam, PennDOT STLRFD.
  - Foundations—Seisab, GRL WEAP, Brass Pier, PennDOT ABUT 5 and ABLRFD, Leap RC Pier LA, Retain Pro.
  - Other—STAAD, STRUDL, AASHTO Ware, and PennDOT Box.
- Standard Plans
  - Government standards—West Virginia, Pennsylvania, Iowa, Ohio, Washington, Federal Highway Administration.
  - Industry standards—AISI Short Span Steel Bridge Plans and Software, Standard Precast Structures: ASTM Culverts, ConSpan, Bebo, USDA Standard Timber Bridge Plans, Pre-Engineered Steel Trusses.

BT-6. For the new structures rated in questions BT-1 and BT-2, rank your reasons for your material/structure preferences (percentages shown indicate order of preference).

States, Locals:

17%,	16%	Initial cost	13%,	16%	Life-cycle cost
15%,	15%	Ease of construction	14%,	12%	Familiarity
10%,	11%	Ease of design	5%,	4%	Lack of competition
13%,	11%	Material availability	14%,	14%	Durability

BT-7. In new construction, indicate your preferred type of deck.

States, Locals:

31%,	27%	Cast-in-place reinforced concrete
18%,	23%	Full-depth precast concrete panels
21%,	20%	Precast concrete elements with CIP topping
13%,	18%	Timber decking
17%,	13%	Steel grids.

BT-8. What types of bridge railings do you use?

States, Locals:

89%,	48%	Concrete “Jersey Barriers”
47%,	42%	Timber railing
83%,	77%	Post-and-beam steel rails
18%,	9%	No railings.

BT-9. Substructure units:

List in the order of priority the preferred type of construction for a new or replacement abutment or pier (percentages shown indicate order of preference).

	Abutment (States, Locals)	Pier (States, Locals)
Cast-in-place concrete	53%, 27%	48%, 28%
Steel piles and lagging		
Timber	5%, 12%	4%, 11%
Concrete	3%, 17%	4%, 17%
Timber piles w/timber lagging	3%, 11%	2%, 12%
Sheeting	3%, 10%	
Pile bent:		
Steel	31%, 15%	34%, 21%
Timber	3%, 8%	8%, 11%

BT-10. For all new structures crossing a waterway, would a pile foundation be required for all sites except those where rock is found at or near the proposed bottom of footing elevation?

States:	81%	Yes	19%	No
Locals:	72%	Yes	22%	No

BT-11. What other types of scour protection do you use for new or rehabilitated structures?

	Yes (States, Locals)	No (States, Locals)
Sheeting	44%, 66%	50%, 34%
Stone fill	94%, 97%	6%, 3%
Stream bed liners	50%, 19%	39%, 81%
Articulated concrete block pavers	33%, 6%	50%, 94%
Increased cover depth to the bottom of footing	89%, 80%	6%, 20%

BT-12. For bridge replacement projects over waterways, is a hydraulic analysis usually completed? If not, what type of hydraulic evaluation of a site is completed?

States:	100% Yes	0% No
Locals:	88% Yes	9% No

- Responses indicate use of WSPRO, HEC RAS, TR 20, and TR 55 procedures. For cases where hydraulic analysis is not conducted, historical assessment of flooding at the site is used with maintenance or enlargement of the opening where possible. Scour is investigated as a potential indicator of flow problems.

BT-13. Do you feel that your geographic area plays a large part in the selection of bridge types?

States:	67% Yes	33% No
Locals:	59% Yes	36% No

- Geography, geology, and material availability were all cited as strong influences in the selection of structure types. Other issues cited included climatic influences such as freeze–thaw, road salting and flooding, and the availability of appropriate equipment for construction of various types of structures.

MAINTENANCE

MA-1. Again with all factors being equal with regards to geometrics, do you favor one type of construction over another due to maintenance consideration? Please indicate order of preference:

States,	Locals:	
18%,	14%	Structural Steel (rolled shapes, plate girders, truss, etc.)
16%,	19%	Reinforced Concrete (T-beams, slab bridges, etc.)
22%,	21%	Concrete Box Culverts (precast and CIP)
12%,	15%	Structural Pipe/Steel Arch Culverts
22%,	19%	Prestressed Concrete (I-beams, boxes, slabs, etc.)
8%,	11%	Timber (glulam and sawn beams, glulam deck bridges, etc.)
1%,	1%	Other

MA-2. Have you determined a means by which you compare the increased first cost vs. increased/more frequent maintenance costs (life-cycle)? If so, please give some examples or details.

States:	0% Yes	100% No
Locals:	12% Yes	84% No

MA-3. What are the biggest maintenance concerns and those that require the greatest amount of resources? (Please rank in order; 1 being the greatest concern, etc.)

States, Locals:

25%,	23%	Decks
19%,	17%	Bridge Superstructures
16%,	19%	Bridge Substructures
17%,	20%	Bridge Railings
17%,	20%	Scour Protection
6%,	1%	Other (specify)

MA-4. Please elaborate on the types of problems described in the answer for MA-3.

- Deck Maintenance—salt deterioration, potholes, deck delamination, extensive patching vs. replacement is a difficult choice, typical damage is to non-coated reinforced decks, worn timber decks.
- Superstructure Maintenance—failed deck joints, corroded beam ends, overheight vehicle impact damage, paint failures, section loss on bridge girders.
- Substructure Maintenance—scour damage, abutment and pier movement, footing undermining, damage to concrete under deck joints, bearing deterioration, failed substructure sheeting.
- Railing Maintenance—upgrading of railings for safety reasons, snow plow damage to bridge rails, collision damage.

MA-5. Please describe procedures used to reduce maintenance needs.

- Many procedures were described. They have been summarized in the body of the report.

MA-6. What methods are used for bridge load rating? (percentage using each method).

States, Locals:

88%,	83%	Empirical methods (i.e., *Manual for Condition Evaluation*)
61%,	19%	Computer modeling
17%,	13%	Load testing

If methods other than the traditional MCE methods are used, why are they used? Are they cost-effective?

- Responses indicate use of load testing for structures difficult to rate (i.e., stone arches, railroad car bridges) and for bridges whose capacity is anticipated to be higher if tested than predicted analytically.

MAINTENANCE AND REHABILITATION OPTIONS

MR-1. When considering off-system bridge replacements, are the bridges designed in-house or by consultants?

States:	61%	In-house	72%	Consultants
Locals:	44%	In-house	56%	Consultants

Are they pre-engineered with a set of standard plans?

States:	22%	Yes	78%	No
Locals:	45%	Yes	55%	No

Briefly discuss your engineering process for replacement bridges.

- Summarized in the body of the report.

MR-2. Is consideration given to using pre-engineered (States, Locals)

	Yes	No
Deck replacement system	39%, 43%	56%, 57%
Superstructure system (i.e., Bebo, Con/Span, Bailey Bridge, Inverset, etc.)	72%, 55%	28%, 45%

MR-3. Do you stockpile components from removed bridges for reuse with future maintenance and rehabilitation work?

States:	67%	Yes	33%	No
Locals:	71%	Yes	29%	No

What types of components are salvaged and reused?

- Primary recycled components are bridge superstructure items such as grid decks or bridge beams. One respondent indicated recycling of metal pipe culverts. Additionally, there are numerous citations of reuse of railings and railing hardware. Some respondents indicate recycling not done since removed items are the property of the contractor.

MR-4. What types of rehabilitation/strengthening work have you performed and what resources were used?

Percentage that Perform	Own Resources	By Contract
89%, 81% Deck Replacement	33%, 62%	78%, 40%
83%, 62% Deck Overlay	33%, 23%	78%, 50%
89%, 53% Deck Joint Replacement	50%, 24%	89%, 37%
83%, 71% Painting	39%, 45%	78%, 48%
89%, 88% Railing Replacement	50%, 75%	83%, 45%
78%, 64% Main Member Replacement	33%, 44%	78%, 32%
89%, 86% Substructure Repair	50%, 65%	89%, 53%
67%, 59% Strengthening	39%, 41%	61%, 34%

Briefly describe strengthening system employed.

- Various rehabilitation methods were described. The most commonly cited included coverplating of existing structures, addition of helper beams, construction of new intermediate bents to shorten spans, post-tensioning of superstructures and substructures, and development of composite action for previously noncomposite bridges.

MR-5. Have you developed any innovative means for rehabilitation/strengthening?

- Replacement of fouled fill over stone spandrel arches with lightweight concrete and minor reinforcing, reuse of removed structures at locations with lesser load demands.

DESIGN CRITERIA AND FUNDING

DCF-1. We believe that the results of this survey will identify a national need to initiate an effort to develop the following for lower volume roadways:

- Revised design criteria
- Revised geometric design criteria
- Innovative designs and structure types
- Standardized plans
- New funding initiatives
- More flexibility with regards to the use of existing funding.

Can you identify any other initiatives that you feel should be included?

- A number of responses indicated that the environmental process needs refinement as it applies to low-volume/ off-system bridge projects. There were also requests for updated standard plans for low-volume road bridges and bridge railings.

DCF-2. Do you have any recommendations regarding existing funding programs such as matching funds and "soft match" funding?

- Other than general requests for more funds, there is a general request for flexibility in the use of federal funds for bridge maintenance and preliminary engineering activities.

DCF-3. If exception criteria for structural or roadway design are not applied to the design of off-system bridges, are there legal liability concerns that influence your agencies decision?

States: 44% Yes 39% No
Locals: 66% Yes 34% No

- Liability is a recognized concern when straying from established AASHTO (or other) standards. Due to the costs of building all structures to modern standards, fewer projects are undertaken.

REGULATORY AGENCIES (Environmental, Historic, etc.)

RA-1. For projects that may involve coordination with various state and/or federal regulatory agencies, what resource(s) do you normally use to complete this effort (percentages indicate use)?

States, Locals:

100%,	84%	Own resources
76%,	83%	Consultants
29%,	14%	Other federal agencies
6%,	22%	Avoid by using 100% local funds
29%,	40%	Other state agencies.

RA-2. Please list any improvements you would like to see with regard to the various requirements of the regulatory agencies.

- Simplified and combined permitting for small projects, relaxation of permit requirements for "in-kind" replacements, relaxed acreage requirements for permit restrictions, and other similar requests were made of the environmental process. Other administrative aspects include accelerated letting of priority projects and a lessening of internal review times.

APPENDIX B

Engineering Software Availability

Free Software Availability

Software Category	Title	Source	URL	Description
Structural Engineering Superstructure Analysis & Design	Alaska Bulb T	Alaska DOT Bridge Section	http://www.dot.state.ak.us	Design of prestressed concrete I-beams.
	BARS-PC	Ohio DOT Structure Rating Group	http://www.dot.state.oh.us/srg/default.htm	AASHTO BARS-PC bridge rating program available for download for use by Ohio consultants.
	BRUFEM	University of Florida Bridge Software Institute	http://bsi-eb.ce.ufl.edu	Finite-element modeling, analysis and rating of bridges using 3-D models. Considers prestressed concrete and steel girders, concrete T-beams, and flat slab bridges.
	CONC	California DOT (Caltrans)—Division of Engineering Services	http://www.dot.ca.gov/hq/esc/earthquake_engineering/CompProg/dosprog.html	Design or analysis of rectangular or flanged reinforced concrete sections for HS 20 loading and Caltrans permit loads.
	LRFD Prestressed Beam Program	Florida DOT Structures Design Office	http://www11.myflorida.com/structures/proglib.htm	Analysis of prestressed concrete beams using the AASHTO LRFD *Specifications*.
	PGSuper	Washington State Bridge and Structures Office	http://www.wsdot.wa.gov/eesc/bridge/software/	Analysis and design of prestressed concrete beams using AASHTO LRFD *Specifications* including stress and stability during transportation.
	Plank for Windows	Colorado DOT Engineering Customer Support Unit	http://www.dot.state.co.us/DevelopProjects/DesignSupport/ecsu/	Computes the rating of plank bridges.
	PSG (prestressed girder)	Colorado DOT Engineering Customer Support Unit	http://www.dot.state.co.us/DevelopProjects/DesignSupport/ecsu/	DOS based program for prestressed girder design using the AASHTO *Standard Specifications*.
	Qcon Bridge	Washington State Bridge and Structures Office	http://www.wsdot.wa.gov/eesc/bridge/software/	Live-load analysis and load combinations for simple or continuous bridges using AASHTO LRFD HL93 loadings.
	RMCalc	Washington State Bridge and Structures Office	http://www.wsdot.wa.gov/eesc/bridge/software/	Restraint moments in continuous prestressed concrete bridges.
	Slab Rating for Windows	Colorado DOT Engineering Customer Support Unit	http://www.dot.state.co.us/DevelopProjects/DesignSupport/ecsu/	Computes the rating of slab bridges.

Free Software Availability

Software Category	Title	Source	URL	Description
	Timber Rating for Windows	Colorado DOT Engineering Customer Support Unit	http://www.dot.state.co.us/DevelopProjects/DesignSupport/ecsu/	Computes the rating of timber bridges.
Structural Engineering Substructure	YIELD	California DOT—Division of Engineering Services	http://www.dot.ca.gov/hq/esc/earthquake_engineering/CompProg/dosprog.html	Analysis of reinforced concrete columns with axial loads and biaxial bending.
	Florida Pier	University of Florida Bridge Software Institute	http://bsi-web.ce.ufl.edu/	Finite-element analysis of bridge piers including pile or drilled shaft foundations and soil-structure interaction.
	NFOOT	California DOT—Division of Engineering Services	http://www.dot.ca.gov/hq/esc/earthquake_engineering/CompProg/dosprog.html	Nonlinear analysis of pile footings including footings with retrofit piles or tie downs for earthquake loading.
	FOOT	California DOT—Division of Engineering Services	http://www.dot.ca.gov/hq/esc/earthquake_engineering/CompProg/dosprog.html	Analysis of spread or pile footings for service, factored, or seismic loading including group loading combinations.
	Drilled Shaft Design	Florida DOT Structures Design Office	http://www11.myflorida.com/structures/proglib.htm	Resistance of drilled shafts founded in sand or clay.
	LRFD Box Culvert	Florida DOT Structures Design Office	http://www11.myflorida.com/structures/proglib.htm	Design of culverts, headwalls, wingwalls, and cutoff walls using AASHTO LRFD.
	LRFD Retaining Wall	Florida DOT Structures Design Office	http://www11.myflorida.com/structures/proglib.htm	Design and analysis of cast-in-place retaining walls using AASHTO LRFD.
	Pile Bent Program	Florida DOT Structures Design Office	http://www11.myflorida.com/structures/proglib.htm	Analysis of fixed and pinned pile bents including lateral loads.
Structural Engineering Miscellaneous	Barlist	Washington State Bridge and Structures Office	http://www.wsdot.wa.gov/eesc/bridge/software/	Reinforcing steel estimating tool.
	BEToolbox	Washington State Bridge and Structures Office	http://www.wsdot.wa.gov/eesc/bridge/software/	Miscellaneous engineering utilities including horizontal and vertical curve elevations, section properties, pile loads in a pile group, precast girder analysis, built-up truss member properties, and biaxial bending capacity of concrete sections.
	Cantilever v. 3.4	Florida DOT Structures Design Office	http://www11.myflorida.com/structures/proglib.htm	Analysis and design of cantilever overhead sign truss structures.
	English High Mast	Florida DOT Structures Design Office	http://www11.myflorida.com/structures/proglib.htm	Design of high mast light poles.

Free Software Availability

Software Category	**Title**	**Source**	**URL**	**Description**
Hydraulics Hydrology	WSPRO	FHWA	http://www.fhwa.dot.gov/bridge/hydsoft.htm	Open channel flow water surface profile modeling. Can be used for flow at bridges, culverts, and for scour computations.
Hydraulics Hydraulic Structures	HY 8 Culvert Analysis	FHWA	http://www.fhwa.dot.gov/bridge/hydsoft.htm	Automated design of hydraulic structures in accordance with FHWA procedures.
	CANDE 89	FHWA	http://www.fhwa.dot.gov/bridge/hyddescr.htm#hy_8_culvert_analysis	Soil-structure interaction analysis for analysis and design of buried structures.
	BOXCAR 1.0	FHWA	http://www.fhwa.dot.gov/bridge/hydsofta.htm#table	Design of reinforced concrete box culverts.
	PIPECAR 2.1	FHWA	http://www.fhwa.dot.gov/bridge/hyddescr.htm#pipecar_2_1	Design of reinforced concrete pipe culverts.
	CMPCHECK 1.0	FHWA	http://www.fhwa.dot.gov/bridge/hyddescr.htm#cmpcheck_1_0	Code check for design of corrugated metal pipes.
Geotechnical	SPT97	Florida DOT Structures Design Office	http://www11.myflorida.com/structures/proglib.htm	Static pile capacity calculator for concrete, H-, pipe, and cylinder piles.
	SPile	FHWA	http://www.fhwa.dot.gov/bridge/geosoft.htm	Determines ultimate vertical pile capacity using various methods.
	Embank	FHWA	http://www.fhwa.dot.gov/bridge/geosoft.htm	Computes settlement under embankment loads.
	CBear	FHWA	http://www.fhwa.dot.gov/bridge/geosoft.htm	Bearing capacity analysis of shallow foundations.
	COM624P	FHWA	http://www.fhwa.dot.gov/bridge/geosoft.htm	Laterally loaded pile analysis.
	MSEW	FHWA	http://www.fhwa.dot.gov/bridge/geosoft.htm	Analysis and design of mechanically stabilized earth walls.
	RSS	FHWA	http://www.fhwa.dot.gov/bridge/geosoft.htm	Analysis and design of reinforced soil slopes.
	ReSSA	FHWA	http://www.fhwa.dot.gov/bridge/geosoft.htm	An updated version of RSS to compute stability of reinforced slopes using various methods.
COGO	CDOT Bridge Geometry	Colorado DOT Engineering Customer Support Unit	http://www.dot.state.co.us/DevelopProjects/DesignSupport/ecsu/	Three-dimensional bridge geometry program.
	Colorado DOT COGO	Colorado DOT Engineering Customer Support Unit	http://www.dot.state.co.us/DevelopProjects/DesignSupport/ecsu/	Coordinate geometry program that interfaces with AutoCAD.

Abbreviations used without definition in TRB Publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation