The Need for Conducting Forensic Analysis of Decommissioned Bridges

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16. Abstract
A limiting factor in current bridge management programs is a lack of detailed knowledge of bridge deterioration mechanisms and processes. The current state of the art is to predict future condition using statistical forecasting models based upon historical observations. This approach is limited in that the historical observations are subjective visual observations assigned to categorical condition states. While this is adequate for routine bridge maintenance and management, it does little to add to fundamental knowledge of the processes that, in the end, limit the useful service life of a bridge. Normal practice is to demolish and dispose of a bridge that is to be replaced, with no attempt to extract useful knowledge from the decommissioned bridge. This project was based upon the hypothesis that bridges which have been in service for extended periods will have deteriorated and that detailed forensic analysis of such bridges can provide fundamental knowledge of the deterioration mechanisms that limit bridge service. This hypothesis was examined and it was found that the current level of understanding of the causes for bridge failures and the factors which limit bridge service life are inadequate to support a project which would focus on forensic analysis. The project focus shifted to better understanding and documenting bridge deterioration and service life prediction. This report documents bridge deterioration and service life prediction models developed for this project.

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Problem Statement

The nation's current approach to civil infrastructure management is not sustainable. The American Society of Civil Engineers, in its most recent report card, assigned an overall grade of D+ to America's infrastructure and estimated that more than $3.6 trillion is needed just to maintain a state of good repair [ASCE 2013]. This figure has increased from the $2.2 trillion estimated in the 2009 report card and does not include the investment needed to increase capacity or put new infrastructure into service. Clearly, the country is losing ground. It is not sufficient merely to recognize the problem or even to establish national priorities and actions to deal with the backlog, as vital as these steps are. A new paradigm must be established for the management of civil infrastructure, and in particular for bridge management. Such a paradigm must take into account the multiple and interrelated factors associated with bridge design, construction, and maintenance. Indeed, the major factor contributing to the current critical situation is that most infrastructures have not been designed and constructed to provide the level of service required. The current approach to bridge management is based upon condition and performance measures that are very subjective and heavily weighted toward ordinal assessments based upon non-quantitative criteria and methods. Past and current practice is to design and construct bridges with almost no regard for adequate inspection, maintenance, preservation, and renewal. As an example, the most common type of highway bridge being placed into service today is a prestressed concrete, multi-girder bridge with a reinforced concrete deck. However, the condition and integrity of the prestressing strands that provide the strength for these bridges cannot be determined once the bridge is placed into service. Additional examples of common bridge elements that cannot be inspected include grouted post tensioning tendons, reinforcing bars, and driven piles. It is also the case that these critical elements cannot be maintained, replaced, or renewed. The current approach to assessing the condition and integrity of such bridge elements is to rely upon visible indications of deterioration. This approach, by design, is reactive and limited to deterioration that has advanced to the point where the element is damaged. Deterioration could, and probably does, exist that has not progressed to the point where visible indications are present. There have been many sudden failures that have been traced back to hidden or latent defects, many of which were directly related to bridges that were not constructed as designed and with materials that did not meet specifications. In addition, there could be deterioration processes occurring that are not yet understood or recognized. All of these factors limiting bridge service life could be better identified, studied, quantified, and understood by conducting forensic autopsies of decommissioned bridges.

1 Approach

A detailed analysis of the available data was conducted to identify the factors which limit bridge service life. The limitations of this approach are presented and discussed, leading to the conclusion that forensic autopsies conducted with a systems-of-systems view are necessary. To fully understand bridge performance, it is considered from the viewpoint of a complex system of systems and by applying risk management principles to identify those factors critical to a goal.

2 Literature Review

The vast literature on bridge infrastructure was explored from the multiple perspectives of bridges as systems of systems, benefiting from the current state of knowledge and practice, transcending multiple disciplines, e.g., structural engineering, systems engineering, risk analysis, economics and finance, material science, and public policy on transportation systems.

The literature on transportation infrastructure maintenance and management has, in the past decade, been concerned with the management of the infrastructure as a system of systems, advocating cross-disciplinary approaches and the use of multiple models. DeLaurentis and Callaway [2004] suggest that complex systems can be understood only through the concept of "horizontal thinking," in which knowledge is obtained from various disciplines. Aktan and Faust [2003] suggest that "there has not been any success in an integrated modeling of infrastructure hyper-systems inclusive of all of their critical engineered, human and natural elements." Furthermore, they suggest that the major challenge is "in adapting and integrating deterministic and stochastic, geometric and numerical, physics-based and 'soft (data-or-knowledge based],' macroscopic or microscopic models developed by various disciplines for simulating infrastructure hyper-systems." Regarding the transportation infrastructure systems of systems, some authors suggest that large-scale transportation systems cannot be adequately represented by purely analytical models [DeLaurentis, 2008], that they cannot be modeled centrally given that local behaviors influence global behaviors, and that the problem is dominated both by physical laws and information processing [Parunak et al., 1998]. DeLaurentis and Callaway [2004] claim that much confusion remains regarding what modeling approach should be used to best deal with transportation infrastructure systems of systems and that "there is lack of systematic thinking at the basic level about how to address the challenges associated with SoS (systems of systems)." DeLaurentis [2008], Lewe et al. [2004], Parker [2010], and Aktan and Faust [2003] suggest that systems of systems problems require a new modeling paradigm that would account for the multiplicity of stakeholders, objectives, interdependencies, and emergent outcomes. Parker [2010] and Aktan and Faust [2003] argue that a reductionist approach that collects many smaller-scale, hierarchically decomposed models into a unified whole is insufficient for the study of systems of systems problems, because it fails to fully capture the intricate interdependencies that can result in emergent outcomes. That is, the reductionist approach assumes that the whole is equal to the sum of its parts, and this is not the case in systems of systems problems. DeLaurentis and Callaway [2004] claim that the "evaluation of an individual entity at its own level is of less importance than how it affects the higher level organization for which it is a member." Thissen and Herder [2009] claim that the "efforts to increase understanding at the overall system of systems level are much needed, in view of the fact that the key performance indicators of [complex infrastructure systems] are in the end determined by the interplay of most, if not all the component systems."

In the transportation infrastructure domain, system dynamics (SD) models have been used to analyze budget allocation policies for highway maintenance programs [Bjornsson et al., 2000; de la Garza et al., 1998] and to study highway management practices [Chasey et al., 1997]. Chasey et al. [1997] use SD to develop a framework that aids in the "the understanding of the relationships between maintenance and construction expenditures on a highway system." In particular, they use SD to identify and quantify a comprehensive level of service for highways that accounts for both the impact of deferred maintenance and highway obsolescence. Shen et al. [2005] use SD to study sustainable performance of construction projects. Haghani et al. [2003] construct an SD model composed of seven sub-models to assess the relationship between land use and transportation system performance. Ozbek et al. [2010] use SD to develop a "comprehensive framework that can measure the overall efficiency of road maintenance operations. This framework is designed to consider the effects of environmental (e.g., climate, location, etc.) and operational (e.g., traffic, load, etc.) factors on such overall efficiency." Kim [1998] utilizes SD to evaluate sustainable highway development. Wang et al. [2008] use SD to model urban transportation systems.

A report by the American Association of State Highway and Transportation Officials (AASHTO) and TRIP [2009] found that traffic growth has far outpaced highway construction, particularly in major metropolitan areas, and the explosion of freight truck traffic is punishing aging highways. Large commercial truck traffic, which places significant stress on pavements, increased 50 percent from 1990 to 2007. Unrelenting traffic, the proliferation of heavy trucks, and deferred maintenance have contributed to the deterioration of America's roads, and sustaining deteriorating roads costs significantly more over time than regularly maintaining a road in good condition. However, the physical mechanisms of pavement deterioration caused by heavy loads are not fully understood. Chatti et al. [2004] investigate the relative damage (fatigue and rutting) on asphalt pavements for different axle and truck configurations using laboratory and field data but find no conclusive results on the effect of axle/truck configuration on fatigue and rut damage when using performance data from in-service pavements.

3 Service Life of Bridges

The service life of existing highway bridges is difficult to determine. The *Status of the Nation's Highways, Bridges and Transit: Condition and Performance* report, published by the Federal Highway Administration, does not provide specific data on this important performance indicator. Therefore, a detailed analysis of the data in the FHWA National Bridge Inventory was performed under this project to identify, to the extent possible, the service life of existing bridges and to identify the factors that limit service life.

The data available include the National Bridge Inventories from 1992 to 2012. However, a separate database of bridges that have reached their service lives is not currently available. A sample of bridges was created by identifying specific bridges that were in service in 1992 and which were replaced between the years 1993 and 2012. Because many jurisdictions assign new structure identification numbers to these replacement bridges, it was not possible to simply identify bridges with the same structure number. The method used was to select bridges that were built after 1992 but carried the same route and facility, intersected the same feature and had the same location as bridges that were in service in 1992. This procedure resulted in a sample of 11,753 bridges. It is recognized that this is not a complete sample of all of the bridges that have been replaced in this 20-year period, because some bridges would have been simply removed from service and others might have been constructed in new locations. However, it is assumed that this sample is large enough to help identify the factors that resulted in these bridges being taken out of service and replaced.

The age at which each of the sample bridges was replaced was determined, and the distribution of these ages (service lives) is presented in Figure 1.

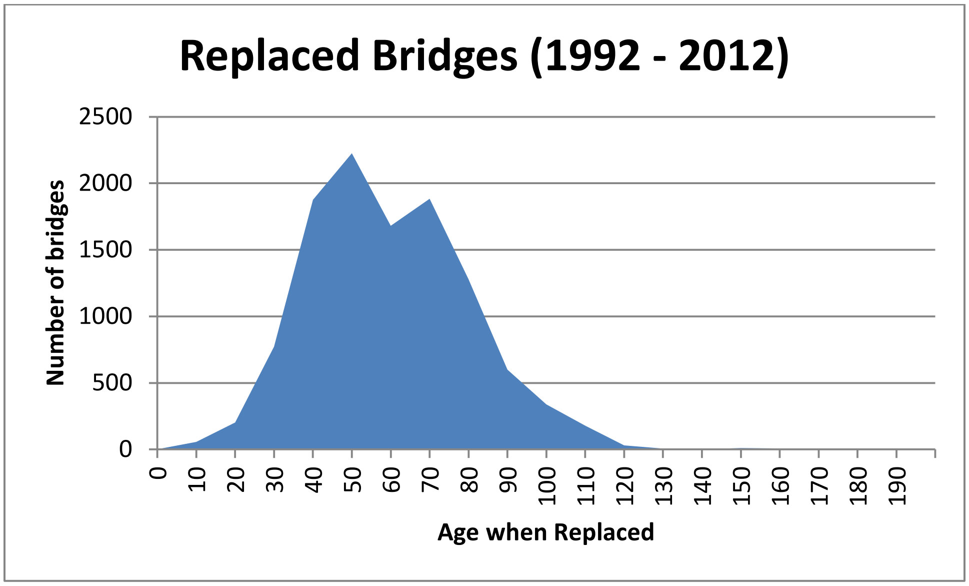

Figure 1. Service Life Distribution

The median service life is 53 years for this sample. This means that almost half of current highway bridges have service lives of less than 50 years. The quartile statistics for service life are presented in Table 1.

Table 1 Service Life Quartile Statistics

First Quartile	Second Quartile	Third Quartile
40 years	53 years	69 years

Current bridge design practice is to attain a service life of 100 years. Clearly, this is a significant increase from existing practice and helps to emphasize the significance of research that will help identify those factors which limit bridge service life.

Current bridge management and inspection practice is to assign subjective condition ratings to major bridge components, to rate the functional performance of bridges, and to classify bridges as structurally deficient or functionally obsolete based upon these ratings. The FHWA definitions of these classifications are provided in Table 2. The item numbers referenced are defined in the FHWA's *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*.

Table 2 Structurally Deficient and Functionally Obsolete Definitions (FHWA Bridge Inspection Coding Guide)

General Qualifications: In order to be considered for either the structurally deficient or functionally obsolete classification a highway bridge must meet the following:

Structurally Deficient -

1. A condition rating of 4 or less for
   - Item 58 - Deck; or
   - Item 59 - Superstructures; or
   - Item 60 - Substructures; or
   - Item 62 - Culvert and Retaining Walls. or
2. An appraisal rating of 2 or less for
   - Item 67 - Structural Condition; or
   - Item 71 - Waterway Adequacy.

Functionally Obsolete -

3. An appraisal rating of 3 or less for
   - Item 68 - Deck Geometry; or
   - Item 69 - Underclearances; or
   - Item 72 - Approach Roadway Alignment. or
4. An appraisal rating of 3 for
   - Item 67 - Structural Condition; or
   - Item 71 - Waterway Adequacy.

Any bridge classified as structurally deficient is excluded from the functionally obsolete category.

An initial look at the proportion of classifications of these replaced bridges helps to begin to examine the factors limiting bridge service life. The proportions of these replaced bridges as classified are presented in Figure 2.

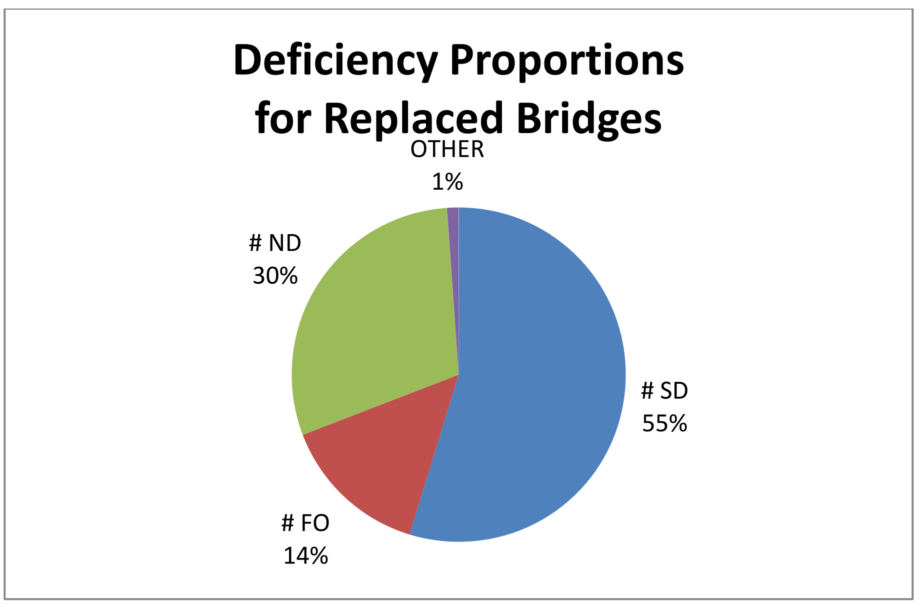

Figure 2 Deficiency Proportions for Replaced Bridges

More than half of the replaced bridges were classified as structurally deficient prior to replacement. Only 14 percent of the replaced bridges were classified as functionally obsolete and, somewhat surprisingly, 30 percent (or almost 1 in 3) of the replaced bridges were not classified as deficient using the above definitions and were therefore assumed to have been replaced for some other reason.

As noted in the definitions for these deficiency classifications, there are a number of ratings which can result in a bridge being classified as deficient. A more detailed analysis of these contributory factors was performed to try to better identify what factors were most significant in limiting bridge service life. A closer look at the structurally deficient bridges that were replaced is provided in Figure 3.

Two factors were most common for these structurally deficient bridges: low load capacity and a substructure in poor condition. Multiple deficiencies are very common. Additional insight into those factors limiting bridge service life was obtained by identifying which combinations of deficiencies existed on these replaced bridges. This information is presented in Figure 4. By far the most common deficiency on these structurally deficient bridges is solely a low load capacity. The second most common was solely a poor substructure condition. These two deficiencies account for almost half of the structurally deficient bridges replaced.

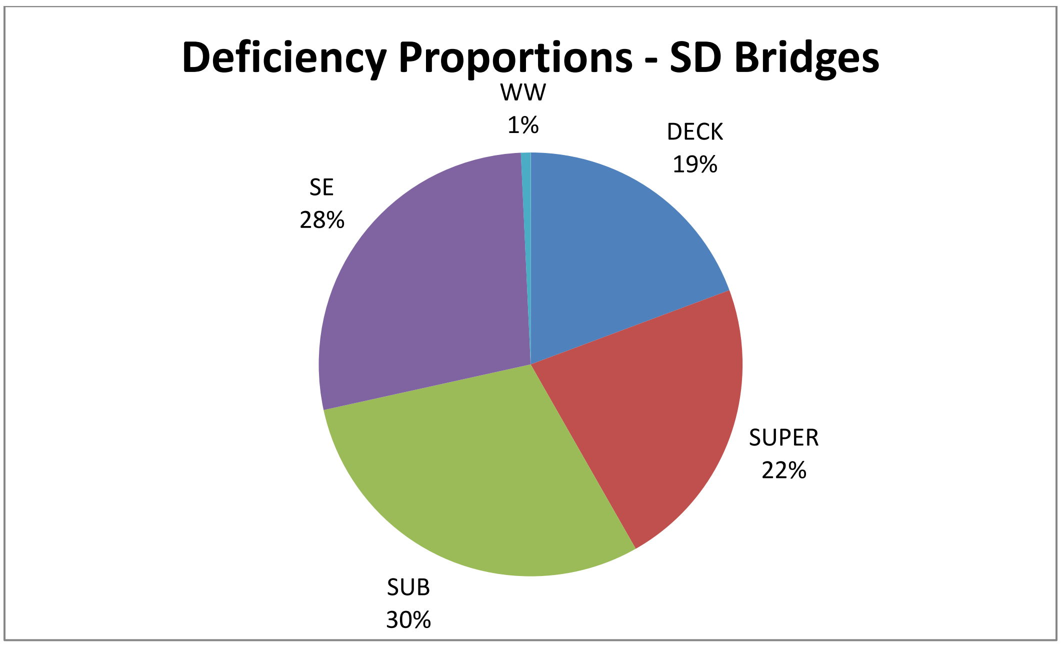

Figure 3 Deficiency Proportions for Structurally Deficient Bridges

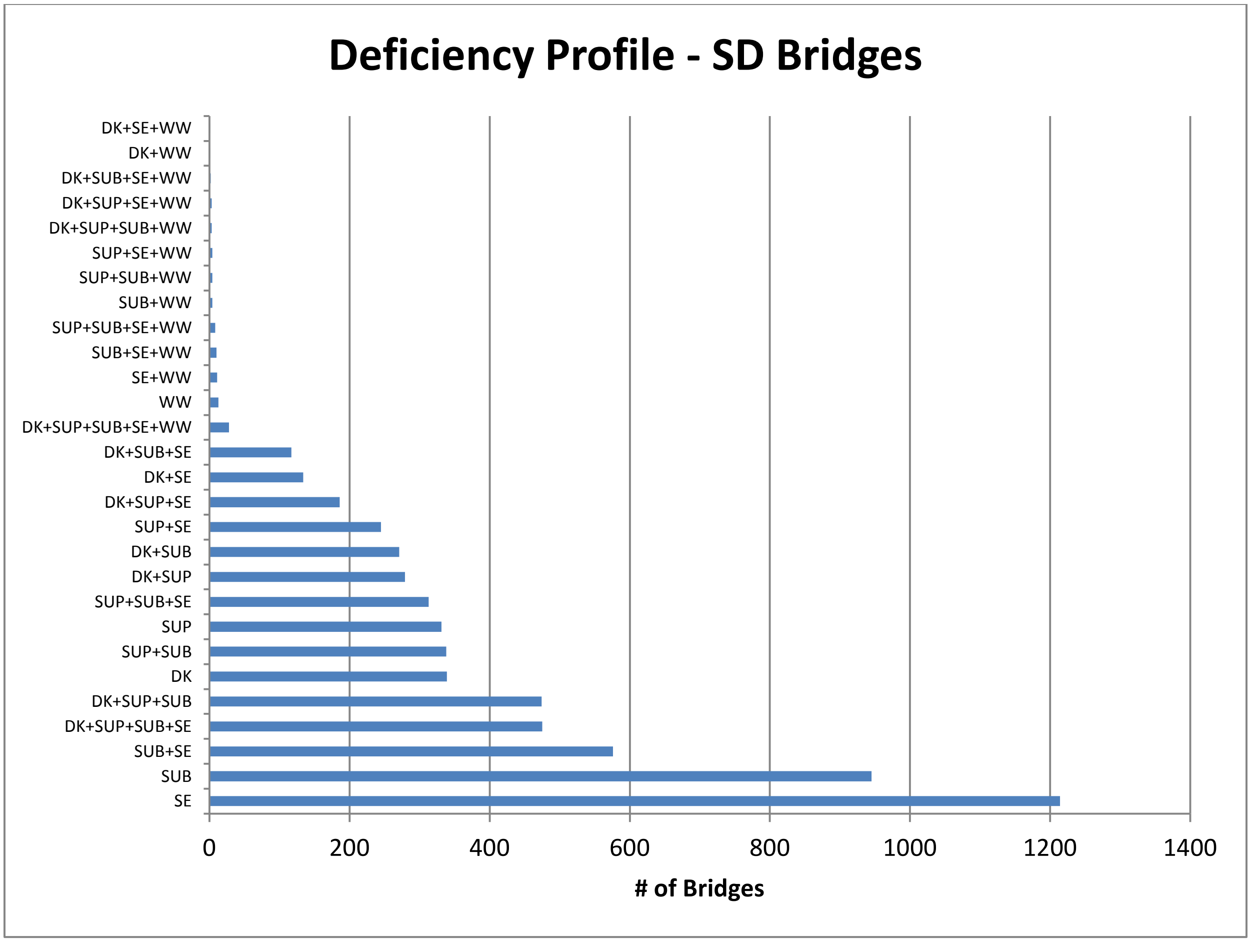

Figure 4 Singular and Combined Deficiencies for SD Bridges

A similar analysis was performed on the replaced bridges that were classified as functionally obsolete. The deficiency distribution for these bridges is presented in Figure 5. By far, the most frequent deficiency in these replaced bridges was a low deck geometry appraisal rating. This means that the roadway width on the bridge is substandard for the system and average daily traffic present on the bridge.

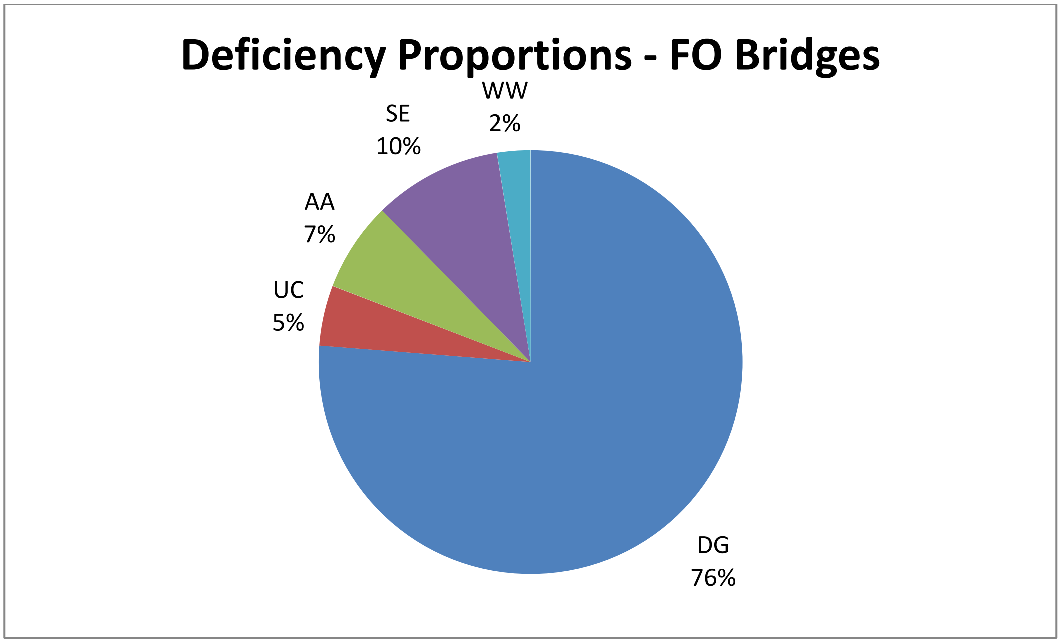

Figure 5 Deficiency Proportions for Functionally Obsolete Bridges

The above analysis provides insight into the factors limiting bridge service life, but further information was provided by looking more closely into the distribution of deficiencies with age at bridge replacement. As shown in Figure 6, the temporal distribution of deficiency classification for these sample bridges provides additional insight.

The most significant observation is that there are bridges which are replaced with less than 20 years of service and that most of these are not deficient. Another observation is that a 100-year service life, the currently desired design objective, is not attained by 98 percent of the bridges in this sample. Clearly, if the current bridge population falls so far short of the desired objective, then a fuller understanding of those factors which limit service life is essential if the desired goal is to be achieved. A detailed analysis of the age distribution for the replaced bridges classified as structurally deficient or functionally obsolete is needed to determine if there were patterns which might provide this additional insight.

The number of structurally deficient bridges replaced in each of the 10-year age groups with specific deficiencies is shown in Figure 7. The predominance of substructure and load capacity deficiencies is reiterated, but there is a fairly uniform distribution of all deficiencies across all ages, with the exception of low waterway appraisal rating (i.e., flooding). The number of functionally obsolete bridges replaced in each age group is shown in Figure 8. The very dominant contribution of substandard roadway width is obvious. This is discussed more fully in the findings section of this report.

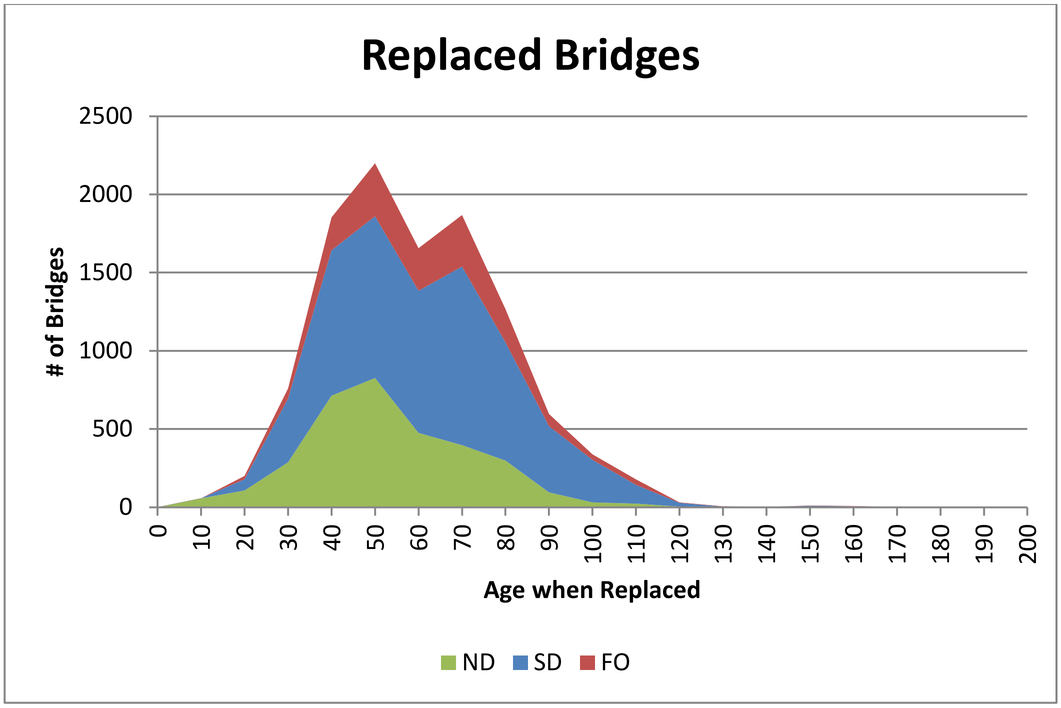

Figure 6 Deficiency Classification By Age at Replacement

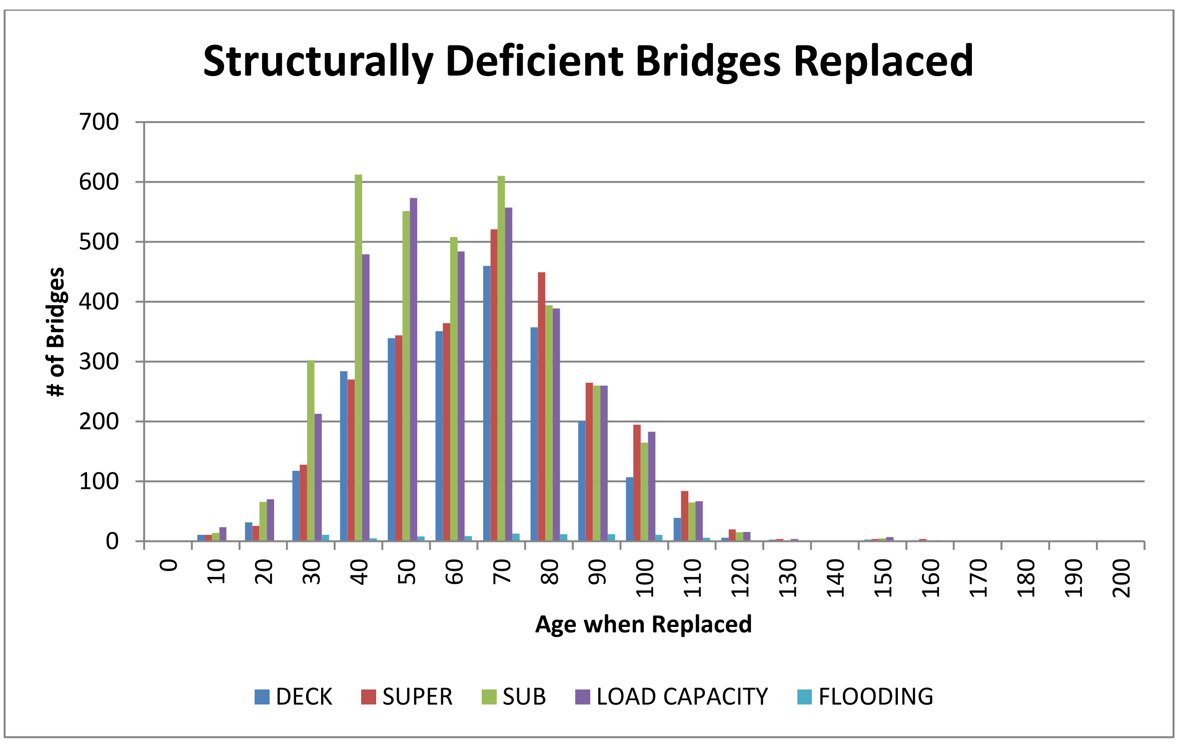

Figure 7 Age Distribution of SD Deficiencies

A significant proportion of the bridges that have been replaced in the last 20 years were not characterized as having any deficiencies. It was assumed that these bridges were replaced for other reasons. The most likely reason conjectured was that the bridges were replaced as part of a roadway widening project or other improvement. If this was the case, then it was hypothesized that the new bridges would be longer or wider than the existing bridges. To test this hypothesis, an analysis of the bridge length, width and total deck area was performed for these replaced non-deficient bridges. The results are presented in Figures 9, 10, and 11.

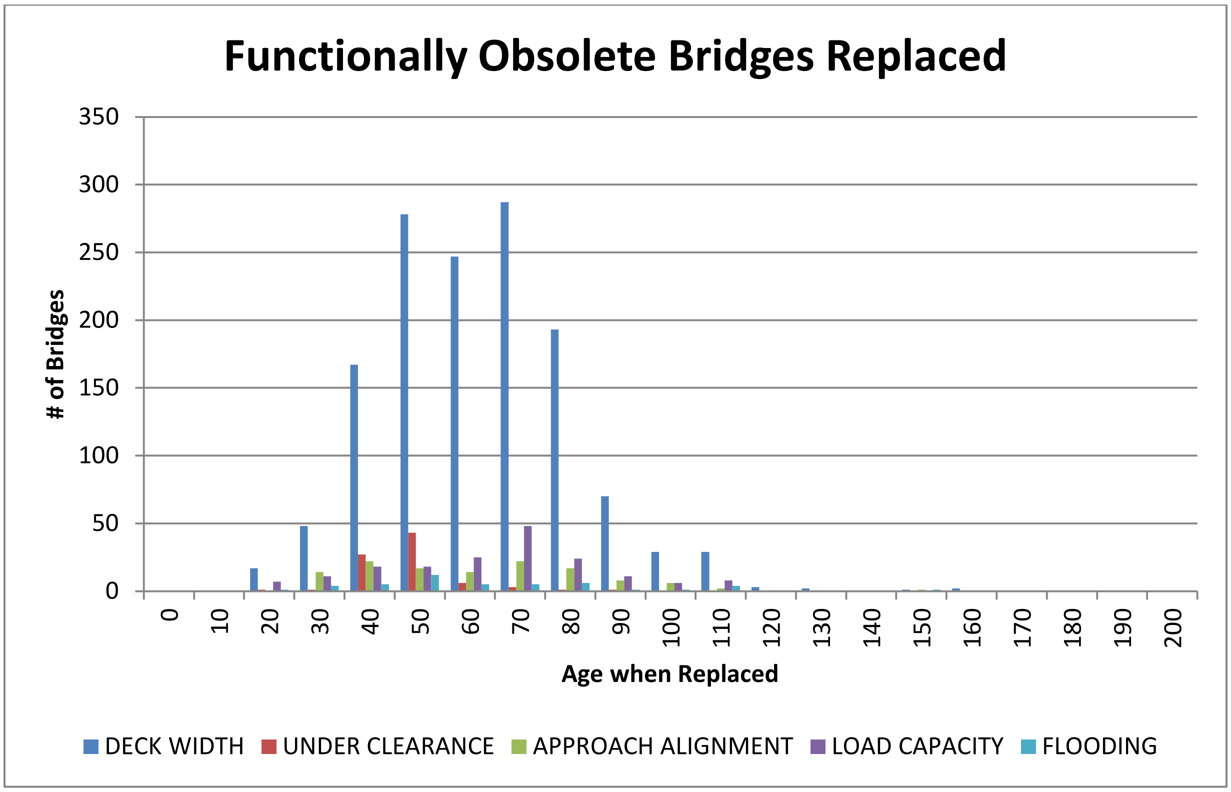

Figure 8 Age Distribution of FO Deficiencies

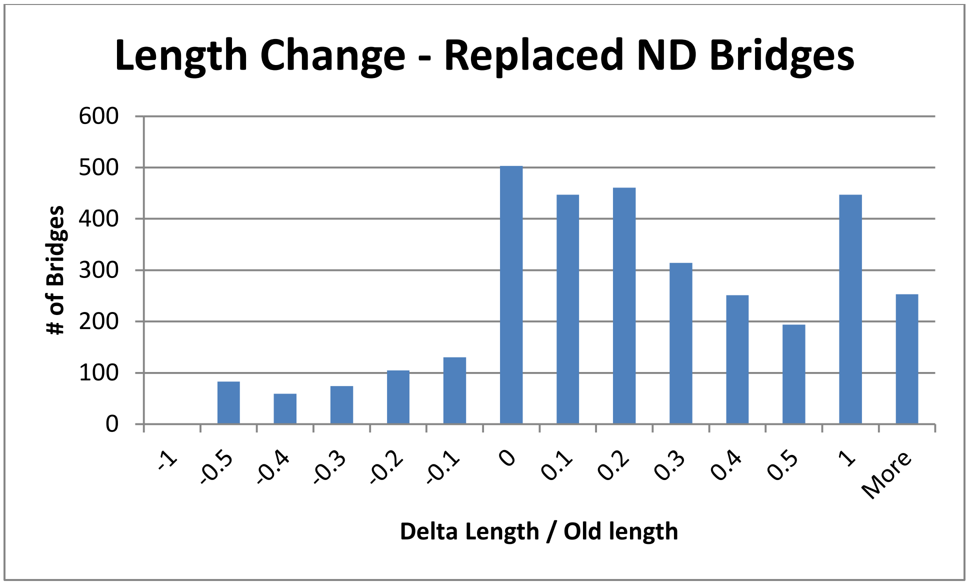

Figure 9 Length Change of ND Replaced Bridges

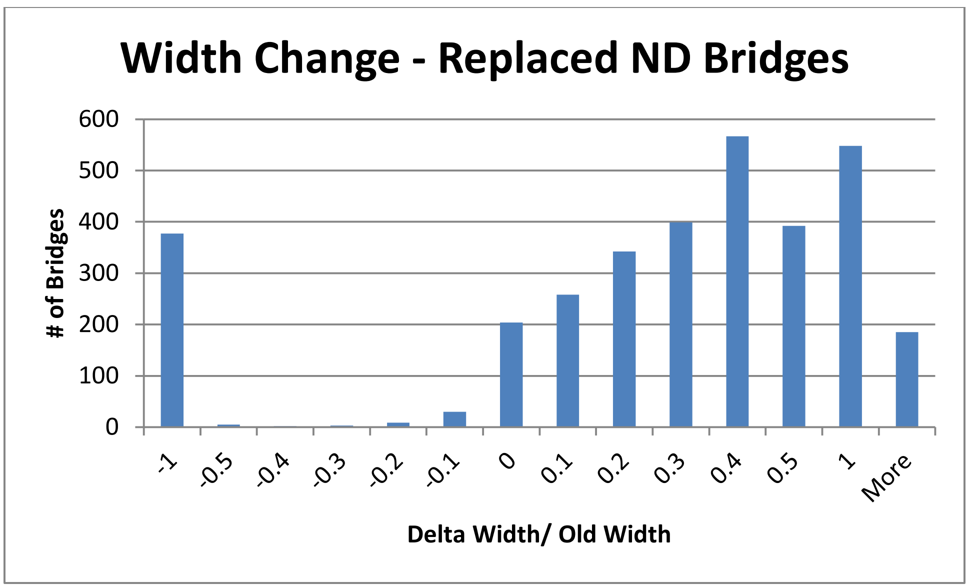

Figure 10 Width Change of ND Replaced Bridges

These results confirm the hypothesis that in the majority of instances the new bridges are longer and wider than the bridges that were replaced. The large numbers of bridges with a significant reduction in width are instances where the new bridge is a culvert with no deck.

It is concluded that the service life of 30 percent of the bridges replaced was limited by the obsolete traffic capacity of the associated roadway.

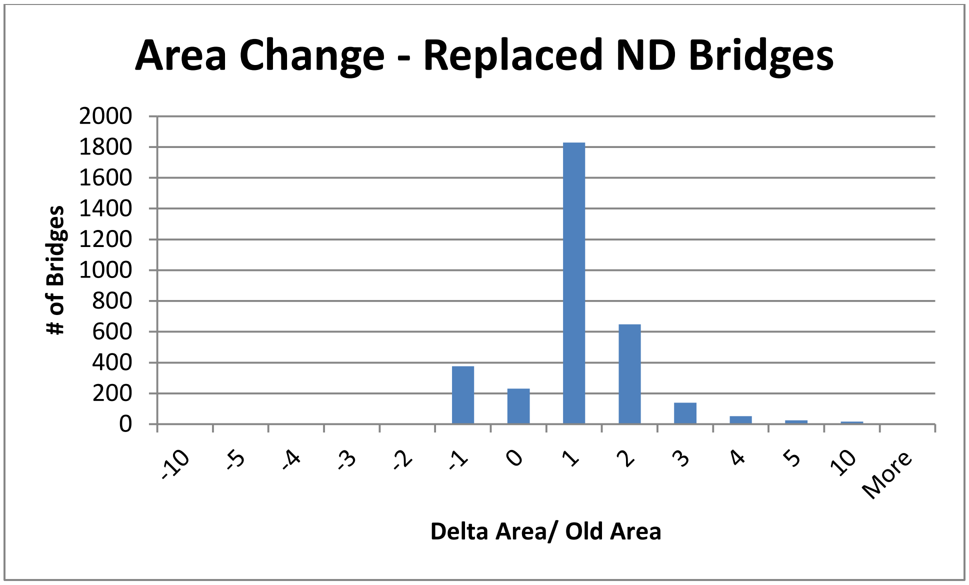

Figure 11 Area Change of ND Replaced bridges

4 Bridges as Physical Systems of Systems

The statistics for bridge service life support the view that bridge service life is limited by physical deterioration, functional obsolescence, and other factors external to the bridge itself. In this section we consider the bridge as a physical system of systems and identify deterioration processes that need to be better understood in order to more fully understand the physical factors that limit bridge service life.

A schematic representation of a typical highway bridge is presented in Figure 12.

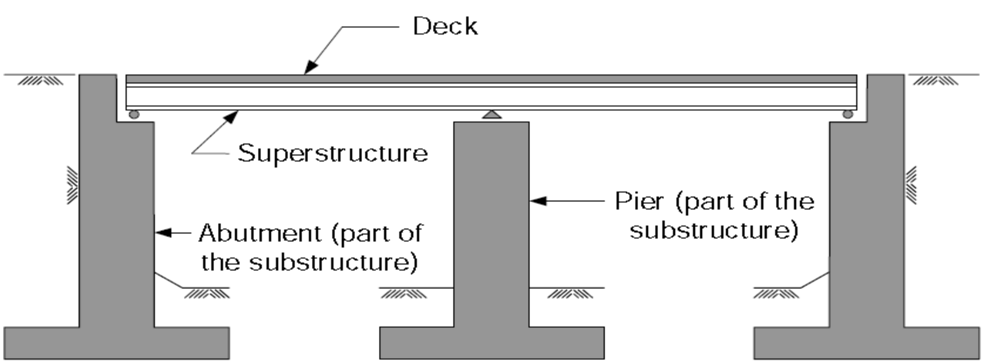

Figure 12 Bridge Schematic

The bridge consists of a substructure, most commonly of reinforced concrete, upon which rest the superstructure and deck. The superstructure transfers the load from the deck to the substructure. The deck is the riding surface and is the component of the bridge system with which the travelling public is most familiar. A variety of materials and structural systems are common on highway bridges and these have changed significantly over time.

As shown in Figure 4, the load capacity of the bridge system is the most frequent factor in limiting bridge service life. Load capacity is usually determined by an engineering calculation based upon the guidance provided in the AASHTO *Manual for Bridge Evaluation*. In summary, the bridge is modeled as a single moment-carrying beam element with span lengths and boundary conditions determined by bridge. The effective width of the beam is determined by formulas prescribed in the AASHTO manual. The stresses and deflections associated with special rating vehicles, positioned to produce maximum effects on the beam, are determined. These are adjusted for dead load effects and safety factors and are compared against limiting values to determine the load capacity of the bridge. If the calculated load capacity is lower than a certain value, the bridge is classified as having a inadequate structural evaluation appraisal, the SE factor shown in the preceding figures. The load capacity of the bridge is very much determined by the initial design of the bridge, and many older bridges were designed for loads which are lower than today's standards. Degradation and deterioration of the load-carrying components of the bridge also result in reduced load capacity. The proportions of the recorded original design load for the replaced bridges are shown in Figure 13.

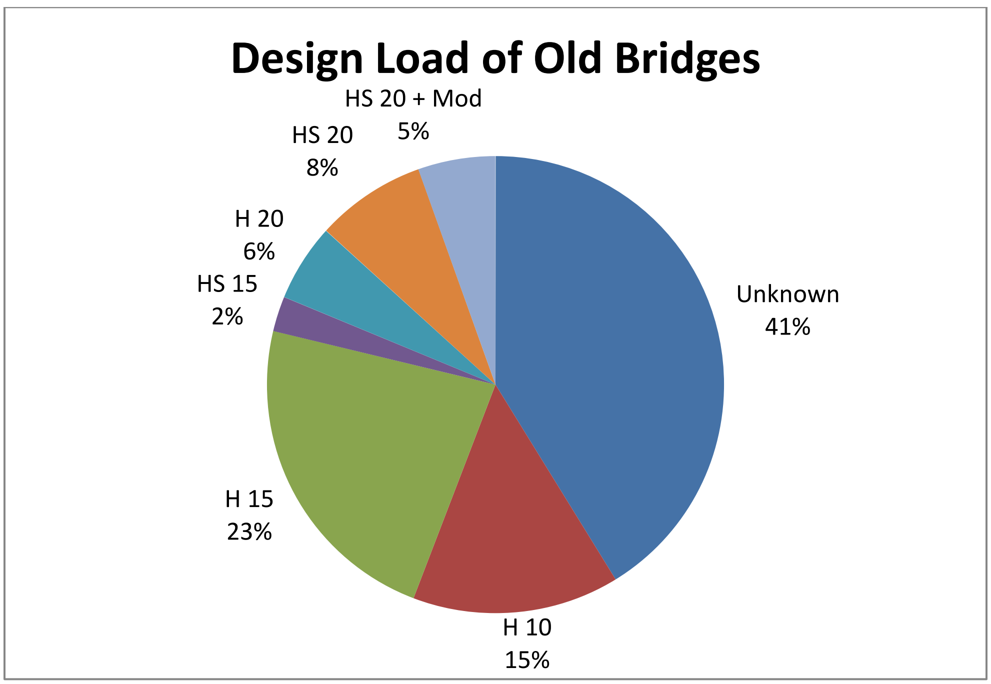

Figure 13 Design Load of Old Bridges

Very significantly, 41% of these old bridges had an unknown design load. In addition, design loads of H 10 and H 15 are well below today's standards, and these bridges are classified as deficient. This draws attention to the fact that the service life of highway bridges is often determined by the original design standards, which become obsolete with time and with the changing expectations of the owners and the public. It also demonstrates that important information necessary for predicting service life is often not available and that alternate methods, such as field measurement, are needed to help manage the inventory of existing infrastructure. While deterioration is certainly an important limiting factor for bridge service life, changing standards and expectations are also very important.

A closer look at the load capacity of this sample of bridges supports this conclusion. The load capacity, of the old and new bridges, as determined by the methods described above, is presented in Figures 14 and 15.

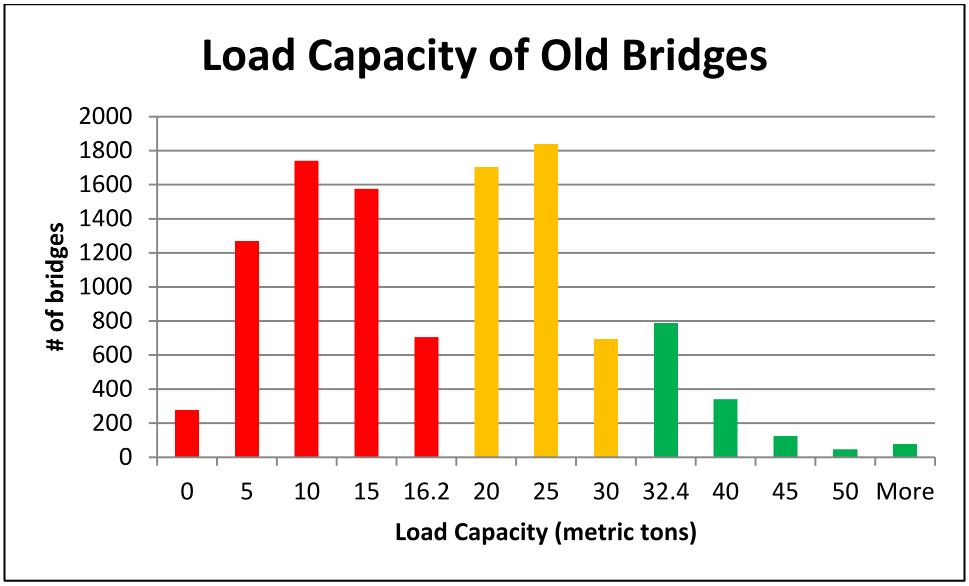

Figure 14 Load Capacity of Old Bridges

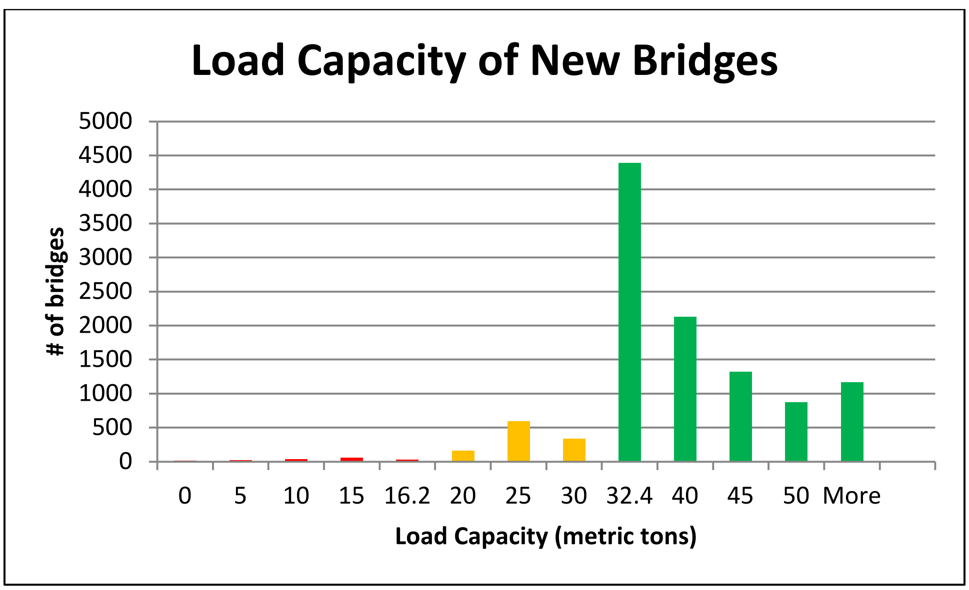

Figure 15 Load Capacity of New Bridges

Half of the old bridges had load capacities below the deficient level of 16.2 metric tons and 95 percent were below the current load capacity standard of 32.4 metric tons for new bridges. Eighty-nine percent of the replacement bridges had load capacities above 32.4 metric tons, as was to be expected. Given the large proportion of bridges with unknown design loads, it was not possible to compare the calculated load capacity with the design load and determine if the low load capacity was due to an old design or deterioration. However, the significant number of structurally deficient bridges with deficiencies other than low load capacity clearly demonstrates that deterioration is a major factor in limiting service life.

By far the predominant materials utilized in highway bridges are steel and Portland cement concrete. This is illustrated in Figure 16, showing the materials used in the old bridges that were replaced.

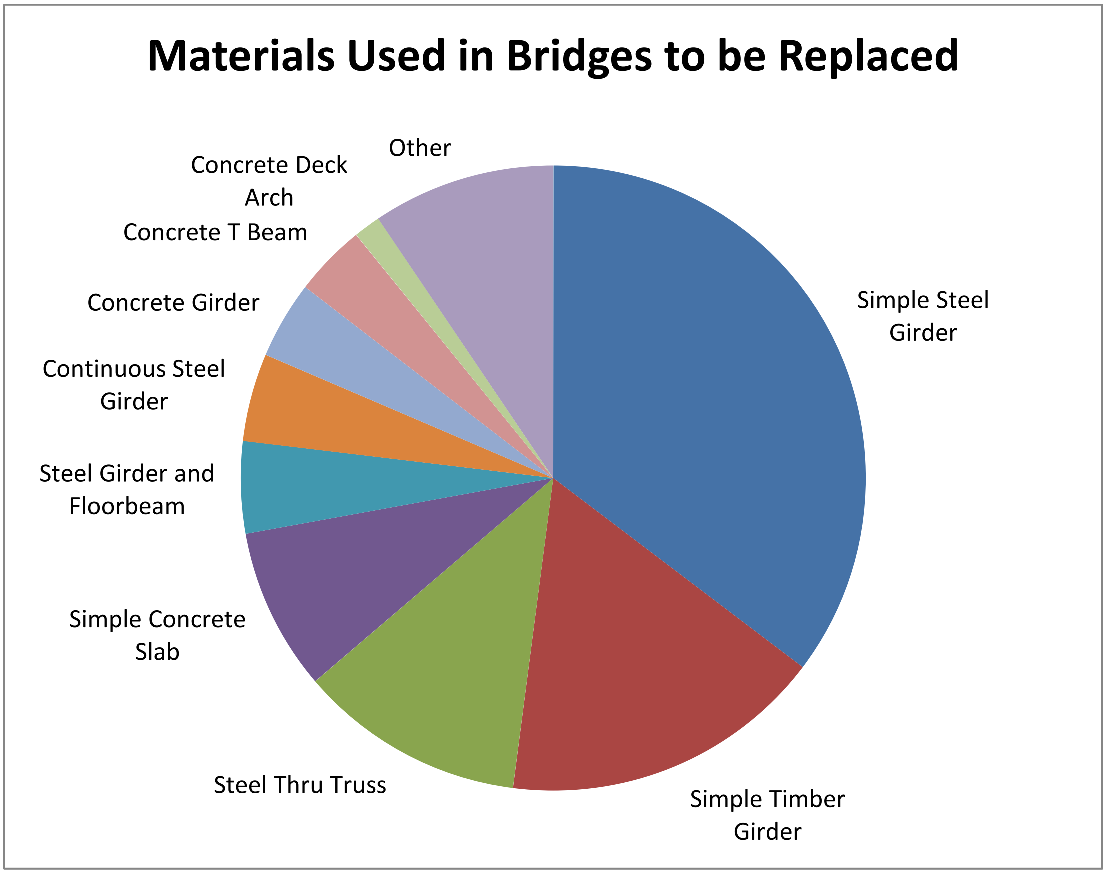

Figure 16 Materials Used in Bridges to be Replaced

The predominance of steel superstructures is noted but most bridge decks and most substructures are made of reinforced concrete. The predominant deterioration mechanisms affecting bridges are corrosion, overloads, fatigue, other environmental attacks, and impact.

A bridge is an interconnected system of subsystems, with the performance of each subsystem often dependent upon the performance of other subsystems. A good example is the effect of leaking joints (a superstructure element) on substructure corrosion. Bridge bearings are often located under joints and corrode if the joints leak. This, in turn, leads to bearings that do not function as designed and leads to very large thermal overloads with temperature extremes.

The performance and service life of a highway bridge is very dependent upon the initial design, but it is also very much dependent upon the bridge being constructed as designed. The fact that the service life distribution in Figure 1 has a large proportion of fairly new bridges might be attributable to substandard materials of details which were not constructed properly. A very common example of this is insufficient cover in reinforced concrete elements.

The analysis of the service life of this sample of bridges has demonstrated that the service life of existing bridges is less than what is desired. The factors that limit service life have been examined as far as possible, given the subjective and non-quantitative nature of the data available in the National Bridge Inventory. The specific reasons for bridges being replaced can only be conjectured and assumed based upon these data. To better understand the factors that limit bridge service life will require a different approach. The approach we propose is to conduct detailed forensic autopsies of decommissioned bridges.

5 Detailed Forensic Autopsies

The data collected under the National Bridge Inspection program are not detailed enough to definitively identify those factors which limit bridge service life. It is also too subjective and unreliable to support quantitative models of bridge deterioration. For example, the NBI does not record the condition of paint systems or joints, or provide information on local damage or deterioration. The data are too general, subjective, and qualitative to be used to develop plans and estimates for repair or rehabilitation work. A more refined approach characterizes a bridge as a collection of elements, such as girders and piers, and records quantitative condition data on each element. Standardized elements have been defined for highway bridges and automated methods are used to translate the element-level data into the NBI data required by the FHWA.

Although the element-level inspections provide more detailed and useful information for network-level bridge management, especially at the state and local level, the information collected is still very limited in several respects. The most significant limitation is that the data collected are based solely upon visual inspection, augmented with limited mechanical methods such as hammer sounding or prying. Visual inspection is highly variable. The FHWA's Nondestructive Evaluation Validation Center's comprehensive and quantitative study of the reliability of visual inspection and the NBI condition rating system shows that a range of condition categorical ratings of 3 or 4 categories can be expected routinely with different inspectors reporting results for same bridge in the same condition. This variability is in addition to the inherent limitation of visual inspection to fail to detect invisible deterioration, damage, or distress.

There are many types of damage and deterioration that need to be detected and measured in order to reliably understand those factors limiting bridge service life as well as determine if a bridge is safe or to decide if repairs are required. Many of these are difficult or impossible to detect visually unless the damage or deterioration is severe. For example, it is not possible to look at a bridge and determine if it has been overloaded or if it has settled unless the damage is so severe as to cause the lines of the bridge to change. Frozen bearings, corrosion, and fatigue damage can exist with no visible indications. Routine visits by bridge inspectors also do not collect information on the operational performance of bridges such as congestion, accident history, or fatigue of structural members. The life cycle of a bridge is commonly described as the sequence of initial construction and the intermittent maintenance, repair, rehabilitation actions ending in the replacement or retirement of the bridge. Clearly, a sequence of actions, the timing and extent of which are based solely upon visual inspections, is very different from a sequence of actions based upon more quantitative and reliable damage detection methods.

The implementations of customer-driven quality improvement programs or asset management supported by true engineering economic analysis are also hindered by the lack of necessary information. We currently guess at average daily traffic values. We do not know the size, number, and weight of the trucks our bridges carry. The actual stresses, strains, deflections, and displacements the bridges experience are unknown. There is a need to more accurately quantify the operational performance of highway bridges. The performance measures, which are most immediate to the traveling public, are concerned with congestion, accidents, and service. These same performance measures can help to quantify the value of a bridge's assets in terms of user costs and benefits. Many of the damage and deterioration processes that need to be better understood at a fundamental level are listed in Table 4.

Table 4 Damage, Deterioration, Operation and Service Processes Quantifiable with Forensic Autopsies

Damage	Deterioration	Operation	Service
Impact Overload Scour Seismic Microcracking Settlement Movement Lack of movement	Corrosion Fatigue Water absorption Loss of prestress force Unintended structural behavior Chemical changes (e.g., ASR, DEF)	Traffic counts Weight of trucks Maximum stress Stress cycles Deflection Displacement	Congestion Accidents Reduced traffic capacity Delay Unreliable travel time Reduced load capacity

Such quantitative measures are also needed to implement true life-cycle cost analysis or performance-based specifications. FHWA, like all federal agencies in the United States, is directed by executive order to consider life cycle cost for major projects. However, the life cycle of bridges has not been defined. The deterioration rates of different materials, structural systems in different environments of loading and climate have not been measured. There is a specific need to integrate quantitative performance measures into the management systems for highway infrastructure. Some of the measurement and detection needs currently not met by our standard practice of visual inspections are tabulated above. These measurement and detection needs exist at many levels and can serve many purposes.

The focus of this report is to document the need for performing detailed forensic autopsies on several bridges each year (out of the several thousand bridges that are decommissioned each year) and to add to the fundamental science and knowledge of bridge engineering. It will be necessary to work closely with the bridge owners, usually State DOTs, to pursue this research. Once a bridge has been programmed for decommissioning, it will be identified as a possible candidate for forensic study. The selection of specific bridges to study will be based upon selection criteria designed to maximize the utility of the data and information which the bridge could contribute. These selection criteria include:

- Potential to quantify deterioration processes, including
    - Atmospheric corrosion of structural steel,
    - Chloride induced corrosion of structural steel,
    - Deterioration of protective systems such as coating systems,
    - Chloride diffusion in Portland cement concrete,
    - Corrosion of reinforcing steel,
    - Corrosion of prestressing steel,
    - Corrosion of bearing,
    - Deterioration of bridge cables and wire rope,
    - Fatigue damage,
    - Alkali silicate reactivity of concrete and
    - Settlement and deterioration of substructure components
- Potential to quantify damage, including
    - impact,
    - overloads,
    - microcracking,
    - settlement and
    - frozen or inoperable joints and bearings
- Potential to quantify operational performance, including
    - Traffic counts, especially heavy vehicles,
    - Weight of trucks,
    - Maximum stresses,
    - Stress cycles,
    - Deflections and
    - Displacements
- Potential to quantify service, including
    - Congestion,
    - Accidents,
    - Reduced traffic capacity,
    - Delay,
    - Unreliable travel time and
    - Reduced load capacity
- Potential to identify episodes of substandard and superior performance and the causes, including

- substandard materials,
- poor construction controls and
- unexpectedly severe environmental factors

The objective of this aspect of the data collection effort would be to quantify damage, deterioration, operational performance, and level of service.

Another very important aspect of the data collection is to identify the specific reasons for the bridge being decommissioned. It has been noted that there are often factors other than physical deterioration which limit bridge service life. Interviews with the bridge owners and other decision makers will be required to identify the institutional and political factors that often lead to decommissioning a bridge. One example is the implementation of HOT Lanes in Northern Virginia, which resulted in the replacement of many serviceable bridges.

This leads to the very important and fundamental finding of this project: Highway bridges exist as systems of systems, as, conceptualized in Figure 17.

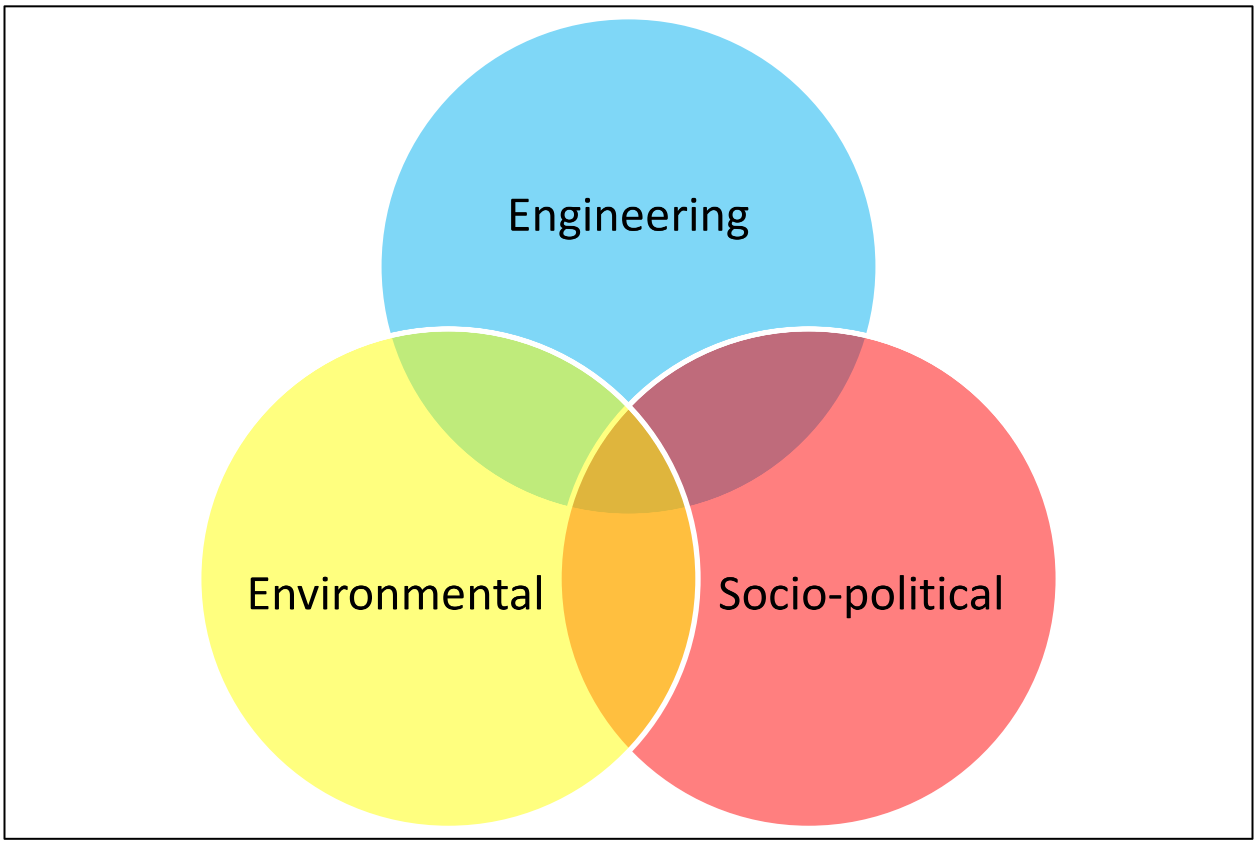

Figure 17 System of Systems

Bridges are engineered systems, and the initial direction of this project was to better understand and quantify bridge service life from that single perspective. However, as we examined the topic in more detail we concluded that highway bridges exist at the nexus of at least three larger systems, the engineering system, the environment to which it is exposed, and perhaps most importantly, the sociopolitical and economic systems which very often are principal in determining bridge service life. A background on the general concept of systems is presented in Appendix A of this report.

6 Summary of Findings and Conclusions

The service life of highway bridges is not well understood or documented. An estimate of bridge service life was developed by identifying a sample of bridges which have been replaced since 1992. This sample was analyzed to determine the most significant factors influencing bridge service life. The median service life of bridges is estimated at 53 years. This is significantly lower that the currently desired 75 to 100 year performance.

The majority of these replaced bridges were structurally deficient but a significant proportion, 30 percent, were not deficient when they were replaced. Functional obsolescence was not a major factor in determining service life.

A low load capacity was found to be the most common deficiency present in these replaced bridges. Poor substructure condition was also a major factor. It is very common that multiple deficiencies exist when a bridge is replaced.

Non-deficient bridges are replaced with bridges that are typically longer and wider than the original bridge. This suggests that many bridges are replaced due to factors other than deterioration and poor performance. The improvement or reconstruction of the associated roadway is the most likely reason for these replacements.

The data available in the National Bridge Inventory lacks sufficient detail and is too subjective and variable to provide the desired understanding and fundamental knowledge about the factors that limit bridge service life.

7 Recommendations

This study has demonstrated that a larger-scale study to identify the factors which limit the service life of highway bridges based upon a systems view of bridge management is needed.

Bridge service life must be studied from the systems perspective in order to fully understand the limiting factors.

A program of forensic analysis of decommissioned bridges could provide currently unavailable and fundamental knowledge of those factors which limit highway bridge service life. This could lead to new understanding, new models, and new methods forming the basis of a new paradigm for bridge management.

A new paradigm is required to manage existing civil infrastructure, and in particular for bridges. Such a paradigm must take into account the multiple and interrelated factors associated with bridge design, construction, and maintenance. Indeed, the major factor contributing to the current critical situation is that most infrastructures have not been designed and constructed to provide the level of service required.

The current approach to assessing the condition and integrity of bridges is to rely upon visible indications of deterioration. This approach, by design, is reactive and limited to deterioration that has advanced to the point where the element is damaged. Deterioration could, and probably does, exist that has not progressed to the point where visible indications are present. There have been many sudden failures that have been traced back to hidden or latent defects, many of which were directly related to bridges that were not constructed as detailed and with materials that did not meet specifications. In addition, there could be deterioration processes occurring that are not yet understood or recognized.

A study of bridge service life, focusing on bridges that are being taken out of service (by definition having reached the end of their service lives) from the viewpoint of bridges as systems of systems, is necessary to fully understand the problem.

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Appendix A. Background – Complex Systems of Systems

The study of complex systems of systems is not familiar to most cCivil engineers. The following sections of this report describe the concepts and the current state of the art in the modeling of complex systems of systems through shared state space and risk management of such systems as an introduction to these topics.

The Role of State Space in the Modeling of Bridge Systems of Systems

Bridges epitomize the criticality of physical infrastructures: they are visible, and we all utilize them, as we cross many bridges while traveling from one location to another. It would be virtually impossible to effectively address the complex lifecycle of bridges (or other physical infrastructures) without models that build on the indispensible domain knowledge of the complexities that stem from the multi-scale composition of bridges—from the physical molecular and macro dimensions, as well as the myriad parties—stakeholders, organizations, the public, and political forces—that determine the fate of our bridges. In this sense, bridges as well as all physical infrastructures constitute complex systems of systems. Models can help answer limited questions about the behavior of these systems under both steady-state conditions and dynamic forced changes. Because each bridge system of systems is comprised of multiple subsystems, each of which, small or large, is characterized by multiple perspectives, it is necessary to develop a set of models to represent this multiplicity; this set of models must reflect the essence of the multiplicity of perspectives, attributes, functions, and dimensions of the bridge systems of systems. Physical, chemical, biological, and other natural laws serve as the first principles and the foundations of such models. Although they are most necessary, these natural laws are not sufficient for model construction. This is because the above-mentioned multiple societal and political perspectives constitute critical driving forces for which all decision-making models must account. Furthermore, the above multiple perspectives cannot be adequately modeled in a single model, a fact that presents a challenge to modelers. Thus what is needed is a mechanism, a systemic framework, with which to augment the natural and physical laws with imagination, inventions, innovation, entrepreneurship, out-of-the-box thinking, and boundless experimentation. This proposed study will build on emerging theory and methodologies for modeling complex systems of systems and their deployment on the bridge systems of systems. The Phantom System Model (PSM) and the PSM Laboratory (PSML), to be introduced subsequently, represent a real and virtual laboratory for such model building [Haimes, 2012].

The essence of meta-model coordination and integration is to build on all relevant direct and indirect sources of information to gain insight into the interconnectedness and intra- and interdependencies among the sub-models, and on the basis of which to develop representative models of the system of systems under consideration. The coordination and integration of the results of the multiple models are achieved at the meta-modeling phase within the PSM, thereby yielding a better understanding of the system as a whole. More specifically, modeling the intra- and interdependencies within and among the subsystems of complex systems of systems requires an understanding of the intricate relationships that characterize the dynamics within and among the states of the subsystems. This very important task is achieved at the meta-modeling level of the PSM by observing, estimating, and assessing the outputs for given inputs, and by building on the intrinsic common states within and among the subsystems. Note that although the intrinsic common states constitute a key element of the PSM, the extrinsic (input-output) relationships are also very important and support the intrinsic one. Indeed, the selection of the trial inputs to the model and the inquisitive process of making sense of the corresponding outputs are at the heart of system identification and parameter estimation. This is not a one-shot process; rather, it can be best characterized by tireless experimentation, trial and error, parameter estimation and adjustments, as well as by questioning whether the assumed model's topology is representative of the system being modeled.

The PSM-based intrinsic meta-modeling of systems of systems stems from the basic assumption that some specific commonalities, interdependencies, interconnectedness, or other relationships must exist between and among any two systems within any system of systems. More specifically:

(i) A system of systems connotes a specific group of sub-systems. A subsystem will denote any system member of the system of systems. A model of a subsystem will be denoted as sub-model.

(ii) A meta-model represents the overall coordinated and integrated sub-models of the system of systems. We define a meta-model as a family of sub-models, each representing specific aspects of the subsystem for the purpose of gaining knowledge and understanding of the multiple interdependencies among the sub-models, and thus to comprehend the system of systems as a whole. For example, the physical structure of a bridge system is composed of multiple subsystems, e.g., a deck and wearing surface, which provides the riding surface and distributes load to the superstructure, the main structural support of the bridge and transfers load to the substructure, and distributes the load to the foundation soils. Each of these subsystems in turn contain and rely upon multiple subsystems such as bearings and joints and various materials such as concrete, structural steel, reinforcing steel, prestressing steel and coatings. (iii) The essence of each subsystem can be represented by a finite number of essential state variables. (The term essence of a system connotes the quintessence of the system, the heart of the system—everything critical about the system.) Given that a system may have a large number of state variables, the term essential states of a system connotes the minimal number of state variables in a model with which to represent the system in a manner that permits the questions at hand to be effectively answered. Thus, these state variables become fundamental for an acceptable model representation.

(iv) For a properly defined system of systems, any interconnected subsystem will have at least one (typically more) shared essential state variable(s) and objective(s) with at least one other subsystem. This requirement constitutes a necessary and sufficient condition for modeling interdependencies among the subsystems (and thus interdependencies across a system of systems). This ensures an overlapping of state variables within the subsystems. Of course, the more we can identify and model joint (overlapping) state variables among the subsystems, the greater is the representativeness of the sub-models and the meta-model of the system of systems.

(v) The importance of the availability of multiple, albeit overlapping, databases can be effectively utilized by multiple sub-models, each of which is built to answer the specific questions for which it is built.

Furthermore, each sub-model's characterization, whether modeled separately or in groups, is likely to share common state variables—a fact that facilitates the ultimate coordination and integration of the modeled multiple sub-models at the meta-modeling level. Thus, a common database that supports the family of systems of systems must be available.

(vi) The fusion of multiple sub-models via the intrinsic meta-modeling coordination and integration enhances our understanding of the inherent behavior and interdependencies of existing and emergent complex systems.

Bridges as Complex Systems of Systems

The U.S. bridge infrastructure is a socio-technical system of systems composed of physical and engineered components, as well as commercial and noncommercial users and decision and policy makers. Bridges are presently managed solely as physical systems and maintenance decisions are usually reactive, and fixes are often short-term (Band-Aid solutions). We note that little to no consideration is given of how current decisions impact future maintenance options or other stakeholders. There are many reasons for lack of proactive maintenance, such as the U.S. political framework, the lack of public accountability and the psychological perception of risk.

Ten Systems-Based Guiding Principles for the Next Generation of Bridge Design, Construction, Operation, Maintenance, and Replacement

By its nature, risk analysis is an intricate, dynamic process—an amalgamation of the arts and sciences—tailored to each specific set of sources of the risks to specific systems. It follows, then, that for any subsystem of the bridge system of systems, the balance between quantitative and qualitative risk analysis will be problem and domain specific. The ten principles we introduce here are intended as an efficacious, valuable risk analysis instrument for guiding the quantitative and qualitative decisions made by bridge engineers and other professionals. Indeed, violations of these basic principles have led in the past to disastrous results in the nation's bridge systems. The idea behind these guiding principles is to provide engineers and other professionals with a checklist that will help them to avoid the most common errors, while still providing them with the flexibility to make appropriate tradeoffs in constructing, deploying, and executing various functions of the bridge system. (For further general discussion of the effectiveness of this approach, see The Checklist Manifesto by Atul Gawande [2010].)

A bridge engineer or a manager might ask: "Why do we need a set of principles to perform risk analysis?" Although no single answer can do justice to this broad question, one may posit that any decision-making process that addresses important probable, including dire, consequences resulting from changes emanating from within or without the bridge systems of systems ought not to be performed on an ad hoc basis. Thus, the lifecycle of the bridge complex infrastructure to be studied and modeled as an systems of systems must adhere to fundamental guiding principles that are cognizant of and responsive to the inevitable emergent forced changes: trends in external or internal sources of risk to a system/project that may adversely affect specific states of that system/project. Examples of emergent forced changes may include elements of the "evolving base," which is characterized by dynamic shifting rules and realities, including: (i) goals and objectives; (ii) stakeholders, decision makers, and interest groups; (iii) organizational, political, and budgetary baselines; (iv) reorganization and reallocation of key personnel; (v) emergent new technology; (vi) requirements, specifications, delivery, and users; and (vii) natural hazards.

The following ten principles guide the proposed study [Haimes, 2012]:

First Principle: Holism is the common denominator that encompasses systems engineering, risk analysis, and effective project management. The bridge system of systems includes the complex physical bridge system; the multiple users—residential and commercial—that add to the load on the bridge system; the constant variability of weather that affects the structural integrity of the bridge system; and the political-budgetary constraints that affect the effective maintenance, operation, and rehabilitation of the physical bridge system. Analyzing a bridge infrastructure system of systems cannot be a selective process, driven by limited perspectives; rather, a holistic systems-based approach must be embraced to account for emergent forced changes; multiple databases and numerous technological and organizational subsystems; multiple objectives, agencies, stakeholders, and decisionmakers; and multiple time horizons associated with each phase in the system lifecycle. These considerations, among others, characterize the modeling challenges associated with systems of systems. Modeling and managing the risk and the lifecycle of bridge infrastructure require understanding the individual behaviors of these components as well as their expected and unexpected interactions.

Second Principle: The process of risk modeling, assessment, management, and communication must be methodical, disciplined, systemic, integrated, and commensurate in its comprehensiveness with the criticality of the systems being addressed and of their associated risks. There are numerous sources of risk emanating from the above subsystems. Furthermore, this process must consider the centrality of the time frame in risk analysis and more specifically, the impacts of the "evolving base" on the ultimate integrity and functionality of the physical bridge system. As an example, consider five categories of emergent forced changes as risk factors associated with the physical bridge system, which constitutes one subsystem of the bridge infrastructure systems of systems: human factors (personnel, culture, and collaboration); technological factors (materials, manufacturing, inspection methods); infrastructure factors (traffic network and corridors, control facilities, and cyber infrastructure); operational factors (maintenance, traffic management, planning and scheduling); and policy factors (regulations, budget, and liability). Because safety is the level of acceptable risk, and no risk to a threatened bridge subsystem can be completely eliminated, tradeoffs are made between the cost of reducing one or more components of the risk vector and of the remaining residual risk. Furthermore, risk analysts (including our team) must be capable of communicating the above reality to the respective stakeholders.

Third Principle: Models and state variables are central to quantitative risk analysis. The integrity and functionality of the physical bridge system are directly related to its states—the levels of corrosion; physical and other structural conditions; and available funds to ensure proper operation, maintenance, and rehabilitation. State variables are essential building blocks of mathematical models, and all decisions aim to change the outputs of the system by changing (or maintaining the current) states of the system. In addition, vulnerability and resilience of the system are also the manifestation of the states of the system. The designed functional objectives and lifecycle management of a bridge can be addressed and ultimately realized, if and only if, the multiple states of each subsystem of the bridge SoS can be identified, modeled, evaluated, and ultimately controlled to meet these objectives. These states include the quality of trained professionals, the quality and reliability of the bridge elements, and the effectiveness of the states of coordination, to cite a few.

Fourth Principle: Multiple models are required to represent the essence of the multiple perspectives of complex systems of systems. Clearly, each of the multiple subsystems that constitute the bridge systems of systems must each be modeled with a specific model to represent the essence of that subsystem of the bridge systems of systems. These models include but not limited to physical models, statistical models, and simulation models. Consider a sample of the dozens of subsystems that constitute the bridge SoS: the physical bridge, designers, manufacturers, inspectors, and maintenance teams. Each requires one or more specific models to represent the essence of each subsystem. Then at a higher level, a holistic meta-modeling approach is used to coordinate different subsystems to achieve effective and efficient management of bridge systems of systems.

Meta-modeling and subsystems integration must derive from the intrinsic states of the system of systems. The extrinsic modeling approach assumes the output of a subsystem becomes the input of another subsystem, while the intrinsic modeling approach assumes that subsystem interdependencies originate from shared states and decisions. Identifying states that are common to multiple subsystems is an important way to understand inter-subsystem interdependencies and interactions. For example, the traffic capacity is a state variable of both engineering subsystem and socio-economic subsystem. The meta-modeling effort takes advantage of the subsystems' models by relating the shared states and decisions among the subsystems, and subsequently coordinating and integrating the information generated from the sub-models into a cohesive representation of the entire bridge systems of systems. To maintain a reliable and sustainable bridge infrastructure system of systems, all its subsystems must function as harmoniously as possible. This challenge can be achieved if and only if there is a clear understanding of the interdependencies and interconnectedness among the intrinsic states of the entire system of systems.

Sixth Principle: Multiple conflicting and competing objectives are inherent in project management. All systems involving stakeholders and decision makers are characterized and driven by multiple conflicting, competing, and non-commensurate objectives; the bridge systems of systems are no exception. For example: (i) minimize all costs associated with the bridge lifecycle; but (ii) maximize quality, reliability, and availability of the bridge system by controlling the traffic load over the bridge and allocating all required resources for its maintenance and rehabilitation. Decision makers must quantify and understand the tradeoffs among different competing objectives and identify non-dominated options. Furthermore, diverse state, federal, and the private sector have an interest in, and an impact on, these objectives.

Seventh Principle: Lifecycle management of systems of systems must account for epistemic and aleatory uncertainties. Uncertainty characterizes most if not all subsystems of the bridge systems of systems. Both epistemic (knowledge) and aleatory (variability) uncertainties must be addressed in modeling, assessing, managing, and communicating the risks associated with the bridge systems of systems. These uncertainties come from both within and outside the system. Examples of epistemic uncertainties include the unknown deterioration process, bridge design error and unknown structural weakness, and prediction for future traffic load. Examples of aleatory uncertainties include the variabilities in (i) environmental factors, (ii) vision inspection results, and (iii) daily traffic.

Eighth Principle: Risk analysis must account for risks of low probability with extreme consequences. Safety-critical systems, especially those that serve the public at large, must account for all sources of risk, and in particular risks associated with a low probability of initiating events with dire and catastrophic consequences. The bridge systems of systems epitomize safety-critical systems. Bridge failure, such as the collapse of bridge is relatively rare event, thus the expected-value metric of risk cannot be applied to bridge system of systems. The failure of bridge not only cause direct property damages and loss of human lives, but also has broader socio-economic consequences due to the interdependencies across multiple industry sectors. The cost of these cascading ripple effects must be estimated and taken into account so that sustainable bridge maintenance activities can be planned under a cost-benefit framework.

Ninth Principle: The time frame is central to lifecycle management of systems of systems. The deterioration of bridge components, the bridge load capacity, the traffic load, and other emergent forced changes, are all functions of time. Understanding the impact of current decisions on future options is an important part of risk analysis. The dynamic nature of all the events—natural and human-made—that affect and impact the integrity and functionality of the bridge systems of systems render the time frame pivotal to risk analysis. It is also critical to consider the variability of the time frames associated with different subsystems. Multiyear bridge lifecycle planning that spans several decades is fraught with unexpected surprises associated with every subsystem. More specifically, the bridge lifecycle planning process is partitioned in sequences of different stages: design, construction, operation, and so on. Clearly, decisions made during design period would constrain and affect subsequent future decisions during construction and operation. In particular, "wrong" or inflexible decisions at any stage could result in programmatic risk (project's cost overrun and time delay in its completion) and technical risk (not meeting performance criteria).

Tenth Principle: Risk analysis must be holistic, adaptive, incremental, and sustainable, and it must be supported with appropriate data collection, metrics with which to measure efficacious progress, and criteria on the basis of which to act. To ensure an effective risk assessment, management, and communication process, a continuous adaptive feedback mechanism must be put in place. Prudent risk management calls for a continuous process of designing a data-collection mechanism, measuring the performance of a system, developing metrics with which to measure performance, assessing whether observed changes are sufficiently significant, and determining criteria for actions—all are requisites for effective risk modeling, assessment, management, and communication. Understanding bridge system behaviors must base upon scientific evidence and credible database. A holistic risk assessment, management, and communication process also guides the need for future data collection.