Leveraging Technology for the Assessment of Highway Bridges

A FORUM Paper

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Introduction

The current practice of bridge condition and load capacity evaluation (i.e. "assessment") in the U.S. can be traced to the 1967 collapse of the Silver Bridge between West Virginia and Ohio. This event led to the Federal Highway Aid Bill of 1968, which required the U.S. Secretary of Transportation to develop a standardized approach for bridge inspection. The National Bridge Inspection Standard (US Congress 1970) followed and provided guidance related to bridge inspector qualifications, inspection and load rating procedures, and the coding of bridge data (descriptive and condition-related) for compliance with the National Bridge Inventory (NBI) database. While the primary reliance on visual inspection procedures remains unchanged from its inception, bridge assessments within the U.S. have evolved due to both bridge failures that brought "new" vulnerabilities to light as well as the desire to use inspection data to better inform bridge management practices.

The first failure to result in a change in the NBIS was the Mianus River Bridge collapse in 1983 that was precipitated by a fracture of two pin-and-hanger details. This failure resulted in the adoption of stricter practices for bridges with fracture critical members and an increase in the frequency of inspections of such members. Four years later, the collapse of the Schoharie Creek Bridge due to scour resulted in the addition of scour assessment and underwater inspection practices. Additional bridge failures, resulting from natural disasters (including the 1989 Loma Prieta and 1994 Northridge Earthquakes as well as Hurricane Katrina), fires, collisions, and the 2007 collapse of the I-35W Bridge, have had little influence over standardized inspection practices, but have influenced new design, certain rating procedures, and have motivated the development of emergency assessment procedures.

In addition to failures, the desire to use bridge inspection data to better support management decisions has played a role in the evolution of assessment practices. Driven by the development of bridge management systems in the late 1980s, some owners began to collect bridge inspection data at a higher spatial resolution than the substructure-superstructure-deck resolution required by the initial NBIS (US Congress 1970). This type of element-level inspection has undergone several refinements over the last two decades, and with the passage of the Moving Ahead for Progress in the 21st Century Act (Neil 2013), has now become a requirement for all bridges on the National Highway System (Slater 1996).

More recently there has been increasing attention paid to the interval for bridge assessments and questions are being raised as to the necessity and cost-effectiveness of requiring every bridge to be inspected every two years. This has led to interest in the development of more flexible risk-based inspection intervals that consider both the probability that condition states will change in a certain interval, and the consequences associated with the change (Washer 2014). While this has yet to be accepted by the community, the concept not only offers a more rational approach to bridge inspection, but also results in reduced costs that may be reinvested into the highest risk bridges or towards the adoption of more accurate assessment technologies.

Although these lines of development have no doubt improved (and continue to improve) bridge assessment practices throughout the U.S., several inherent shortcomings of current assessment procedures remain, which include (a) its subjective nature and variability, (b) its inability to assess deterioration not visible, (c) its inability to reliably trace observed deterioration to root causes to inform interventions, (d) its rather narrow focus on condition/durability limit states, and (e) its view of bridges as a collection of elements without regard for how they interact and perform as a system. Meanwhile the technological revolution of the last several decades has created an entire landscape of sensing, simulation, and information technologies that have yet to be integrated into bridge assessment practice in any systematic or effective way.

As infrastructure policy solidifies its place within the nation's political discourse (and the owners on the front lines continue to struggle with funding shortfalls) the authors believe that the untapped potential of these technologies will emerge as a driver for change no less significant than past failures or bridge management concerns. With the prospect of more flexible, risk-based inspection intervals serving as a potential enabler of this change, the authors believe an open discussion of the value and means of integrating various technologies within bridge assessment practice is quite timely. The goal of this paper is to contribute to such a dialog.

Overview of Bridge Assessment Practice

Bridge assessment practice in the U.S. requires the collection/calculation and reporting of four types of information. The first is the development of condition ratings based on visual inspection. This falls under the purview of FHWA's Office of Infrastructure, Bridges and Structures Office which issues and maintains the National Bridge Inspection Standards (NBIS 2001/2004). While these procedures have evolved over the last four decades as described above, they remain inherently qualitative in nature and are conditioned by an inspector's education, experience, vision, hearing, and safe climbing-reaching skills. More quantitative surveying and scanning with non-destructive evaluation (NDE) tools are referenced when conditions warrant, but their actual use is optional and their deployment is rare.

In addition, during regular inspections, more than 100 inventory items are collected either from past inspection reports, design/as-built plans, or field survey. These items describe both the attributes of a bridge as well some demands. For example, this information includes bridge type and material, overall dimensions, number of spans, average daily traffic (ADT) and average daily truck traffic (ADTT), among others. Inventory items of particular importance are related to the scour and fracture criticality of the bridge, which can influence the type and frequency of required visual inspections.

The third item required is the calculation and reporting of a “load rating” for each bridge, that reflects its capacity to carry live loads. Operating and Inventory ratings are generally based on the analysis of a simple line-girder idealization following allowable stress, load factor or load and resistance factor approaches (Hearn 2014). While the representative nature of such simplified models is debatable, load ratings are noteworthy as they remain the only assessment activity to attempt to quantitatively assess a safety-related limit state based on principles of physics.

The final activity associated with assessment is the calculation and reporting of indices and designations that combine information from the other three information sources to aide in decision-making and resource allocation. These historically have taken the form of Structurally Deficient and Functionally Obsolete designations as well as the computation of the Sufficiency Rating. With the increased popularity (and now requirement) for element-level inspections, the development of indices that combine element-level condition ratings are now becoming more relevant. Examples include the California Health Index and the AASHTO health Index.

Discussion of Current Bridge Assessment Shortcomings

Visual Inspection Practice

Perhaps the most widely discussed shortcoming of visual inspection procedures focus on their subjectivity and variability. This issue was brought to light through a study led by the FHWA NDE Validation Center that compared results from 49 inspectors (selected from 25 states) who inspected the same seven bridges (Phares et al. 2004). The results of this study demonstrated the inherent variability of visual inspection, which reflects the disparate supplemental educational and experience requirements for inspectors across different states. Although it is possible to incrementally improve the variability of visual inspections, given the different resources, cultures, construction practices, and hazards associated with various states, it is unclear how realistic (or even desirable and cost effective) it is to strive towards uniform inspection practices across the U.S.

Another commonly referenced shortcoming of visual inspections is its inability to identify or characterize deterioration that is not visible. This shortcoming has resulted in great interest in the use of various NDE tools to provide some means of sub-surface characterization. In addition, the quantitative/objective nature of such tools is also expected to help reduce the variability of assessments that result from the qualitative/subjective nature of visual inspections. While there are many problems that remain (such as the inspection of bonded pre-stressing and grouted post-tensioning tendons), this field continues to push the frontiers of condition assessment and is enjoying progressively wider implementation in practice.

In addition to these more widely recognized shortcomings, there are two others that are rarely discussed, but the authors believe their relevance is significant. First, while visual inspection can identify visible deterioration, this does not necessarily translate into the identification of its root cause. Without understanding root causes, the design of effective interventions is difficult as attention may focus on symptoms whose treatment has little ability to curb the underlying performance issue. The authors offer the following structure of the coupled influences that may drive the type and extent of bridge deterioration:

1. Initial design (skew, horizontal and vertical curvature; site, soil, foundations and sub-structures; approaches; structural materials; dynamic characteristics, stiffness, redundancy, detailing; bearings and joints)
2. Construction quality (material and fabrication quality, tolerances (e.g. cover), intrinsic forces/fit-up)
3. Environmental inputs (climate and freeze-thaw, weather and temperature fluctuations, precipitation, site conditions, settlements, etc.)
4. Live Load Environment (truck weights, frequencies, axle configurations, speed and dynamics)
5. Maintenance activities (application of de-icing agents, joint/bearing servicing, bridge washing, deck sealing, etc.)

While many of these factors are fairly well understood (e.g., insufficient cover leads to premature deck deterioration; de-icing agents and freeze-thaw exacerbate deck deterioration; trucks and insufficient drainage cause premature joint failure and bearing deterioration, etc.) what is less clear is the role that the global structural characteristics of a bridge play in observed deterioration. Fundamentally, this stems from a reductionist approach in which bridge systems are viewed as disconnected, individual elements (e.g. NBIS, element-level inspection). Such an approach may be efficient, but it suffers from a neglect of emergent, system-level behaviors that result more from element interactions than individual element responses. For example, the deterioration of bridge decks is commonly viewed as resulting from freeze-thaw, de-icing chemicals, rebar corrosion, etc., but this ignores the fact that bridge decks are an integral component of a structural system through which they are also subjected to vibrations, live load actions, thermal variations and gradients, etc.

The recognition of the knowledge gaps associated with how system-level behaviors influence deterioration has fueled interest in "design for durability" that aims to move durability considerations beyond just material and construction requirements. Currently there is little tangible understanding of how, for example, longitudinal and transverse stiffness, operating stress levels, dynamic characteristics, structural form (straight, skew, curved), and vertical/approach profile influence the long-term performance of bridge decks, joints, and bearings (to names a few examples). In addition to new design, these knowledge gaps hamper effective intervention design, and in general cannot be bridged with visual inspection alone as they require the quantitative characterization of various system properties.

The final item is related to the rather narrow focus of visual inspection procedures on assessing performance at the utility/functionality and serviceability/durability limit states. The assessment of such performance limit states is necessary, but not sufficient. Just as in the case of new design, the evaluation of performance limit states associated with safety (or strength) and resilience should be a required component of bridge assessment practice. In contrast to the operational and service-level limit states, performance at the safety and resilience limit states cannot be directly observed. Rather, such an evaluation requires the estimation of likely future performance given a specific bridge system (inclusive of roadway-approaches-superstructure-substructures-foundations-soil), condition states, and hazards.

Although this evaluation is often downplayed due to the expectation that hazards should have been considered in the original design, such a practice fails to consider a number of issues. First, in many cases the original designs did not explicitly consider many of the limit states and hazards that have become commonplace today. This is not to argue that all bridges must meet current design standards, but owners should be aware of any such deficiencies so they may plan accordingly. Second, the initial design may include errors or the actual construction of the bridge may have deviated from the original design. While the former are admittedly rare, the recent collapse of the I-35W Bridge serves as a reminder that the original design should not be blindly assumed to be error free.

Finally, deterioration and/or damage may compromise the expected performance at these limit states. One may argue that visual inspection can properly address this last issue, but this ignores the fact that different bridge systems can accommodate significantly different levels of deterioration and damage prior to influencing safety or resiliency limit states. Current practice aims to consider this through the designation of various elements as “fracture critical,” but there is now growing recognition that such designations do not fully appreciate and incorporate the complete system characteristics and redundancy (Diggelman et al. 2013). In addition, while the assessment of redundancy is clearly important, the tolerance to deterioration and damage is also influenced greatly by both the intentional conservatism (e.g. safety factor, reliability index) as well as the inherent conservatism present due to the use of simplified structural analysis models and other simplifying assumptions during the design phase.

Given the complexity of issues surrounding safety and resiliency limit states, it is unrealistic to expect visual appearance alone to be used as the basis of such an assessment. Current practice recognizes this and requires supplemental activities including scour and fracture-critical evaluation as well as load rating, but these are all patches and the authors believe a more systematic approach that includes a more complete understanding of bridge behavior and performance as a site-bridge-foundation-soil system and how these are affected by various hazards is desirable. While this may require additional resources, given that the likely performance at safety and resiliency limit states evolve slowly with time, their evaluation intervals may be much longer than for operation and service limit states.

Together with expanding assessment to address additional limit states, it is also necessary to bring additional clarity to the relevant limit-states for operating bridges. That is, the loading scenarios and acceptable response/behavior thresholds for each limit state needs to be defined. In addition to allowing performance to be objectively quantified, such definitions will also equip inspectors with scenarios to guide an evaluation of how a bridge may violate such limit states in the future, and thus permit the identification of more pro-active interventions.

Common Load Rating Practice

A recent NCHRP study investigated current bridge load rating and posting practices within the U.S. (Hearn 2014) and found that over 80% of bridges are rated using simplified structural analysis procedures. Given that the study also found that 16% of bridges received no load rating, the use of simplified structural analysis procedures were employed to generate more than 95% of all load ratings reported. In such cases the bridge is typically idealized as a single, static beam through the use of live load distribution factors (which approximate the percentage of a lane-load carried by each girder), skew correction factors, and dynamic load allowance factors. Such approaches have been shown over time to produce conservative designs, but they are not capable (and perhaps were never intended to be capable) of accurately simulating the transverse load distribution of multi-girder bridges, dynamic responses, or the effects of skew.

It follows that while such models offer conservative estimates of load-carrying capacity they are unable to estimate actual structural characteristics and thus fall short in three important ways. First, in cases where a bridge fails to rate, such simplified models cannot be relied upon to accurately identify the governing "critical" member or location (especially important in cases where girder transitions are present). Second, in cases where a bridge is displaying various forms of deterioration, the simplified methods cannot accurately simulate its effects (since many elements are not explicitly modeled), and thus they are forced to rely on the use of subjective reduction factors. Third, such approaches cannot be relied upon to offer accurate estimates of stresses, stiffness (transverse or longitudinal) or dynamic properties, which hampers their ability to be used to diagnose deterioration caused or exacerbated by structural responses.

In addition to these shortcomings, it is important to recognize that single-line girder rating approaches tend to provide rating factors that are highly conservative. As a screening tool, such a method can be quite effective, but in many cases this approach is also employed to post structures, which may unnecessarily hamper commerce or the mobility of emergency vehicles and school buses. The AASHTO Manual for Bridge Evaluation (MBE) 2nd Edition (AASHTO 2008/2011) recognizes this conservatism and allows bridges "that exhibit insufficient load capacity when analyzed with approximate methods" to be "analyzed by refined methods of analysis." Further, the AAHSTO MBE (2008/2011) allows bridges to be rated by "field testing (load testing) if the evaluator feels that analytical approaches do not accurately represent the true behavior and load distribution". Although such methods are available to practicing engineers, they are rarely employed. For example, Hearn (2014) reports that less than 0.1% of bridges are rated based on load testing procedures, even though over 10% of bridges in the U.S. are posted for less than legal loads.

Current Load Testing Practice

The origins of standardized field testing procedures can be traced to NCHRP Project 12-28(13), which was initiated in 1987 to develop guidelines for "nondestructive load testing of highway bridges". This project was extended and culminated in a manual for "bridge rating through nondestructive load testing" in 1994. The AASHTO MBE (2008/2011) with 2013 Interim Revisions (2013) incorporates the approach outlined in this manual as an approved means of supplementing analytical procedures in determining live-load rating factors and for validating modeling assumptions. This approach recognizes two types of nondestructive load testing: diagnostic- and proof-level. These tests are distinguished generally by the level of load, with diagnostic-level loads near service loads and proof-level loads closer to design loads.

While proof-level tests are conducted using statically positioned trucks or other special devices to generate the load levels required, diagnostic-level tests can be carried out using static or crawling trucks, operating traffic, or vibration testing techniques.

Perhaps the most striking shortcoming of the practice of load testing is related to its very sparse implementation (as mentioned previously). Consider that over 61,000 bridges are currently posted for less than legal loads, but fewer than 600 bridges nationwide have been rated using load testing procedures (Hearn 2014). This reflects that owners do not consider load testing an attractive value proposition. This no doubt stems from the cost associated with such tests (which may range from 5 to 10 times the cost of a visual inspection), but it is likely also fueled by the narrow benefits obtained by such tests related exclusively to load rating. While technologies may mitigate the cost issue, the value issue must be addressed through expanding the focus of load testing to characterize various structural properties, which may be used to both diagnose the root causes of various forms of deterioration and forecast their future propagation.

In addition to its limited use and lack of integration with other bridge assessment activities, there are three more specific shortcomings of the current load testing guidance. The first involves the lack of specific guidance and requirements as to what constitutes an acceptable load test. For example, current guidance is silent on the minimum personnel requirements/training needed to carry out a load test, the number and type of measurements that must be acquired, the type and details of simulation models used to support the test, the means of model-experiment correlation, approaches for error screening and data processing, etc. Although it is conceded that a process-based guide that dictates all such decisions is unrealistic due to the unique aspects of operating bridges, without some minimum requirements the load testing of bridges is susceptible to ill-designed applications that have significant potential to be misleading and unreliable.

The second key shortcoming is related to proof-level testing, and in particular, the fact that such a load test (which may apply enormous static loads to a bridge) may be carried out without the benefit of any simulation model. The manual does mention that the test should be stopped at the first sign of distress, but this ignores the difficulty in first completely determining and then observing all critical regions and incipient failure modes during a test. Further, without the requirement of a realistic simulation model (one that explicitly simulates all key load-carrying mechanisms) it is difficult to accurately identify potential critical areas and thus instrumentation cannot be reliably used to supplement visual observations during the test. Taken at face value, this approach creates a dangerous precedent that is tantamount to the manner in which the Romans proof tested bridges millennia ago.

The third shortcoming is more subtle in nature and involves the manner in which diagnostic test results are used to update rating factors. The manual recommends that members that do not rate be instrumented during the diagnostic test and that the rating factors be updated based on the ratio of the measured and predicted responses (by the model used for rating, typically a single-line girder model). While the manual does provide a factor that represents how well the experimental data is correlated with "theory," no rational approach for the selection of such a factor is provided. This approach amounts to "correcting" a highly idealized, conservative, but non-representative model with response data measured from a bridge with no explanation of why the two differ (in many cases significantly). That is, the current approach does not recognize the importance of identifying all of the mechanisms that are responsible for differences between the model and measured response. This raises serious questions as certain mechanisms (frozen bearings and joints, participation of barriers in longitudinal bending, etc.) may not be reliable over the long term and thus should be ignored for rating purposes. Since the participation of such mechanisms is implicit in the experimental data, the use of a model which represents all such mechanisms must be properly correlated with the response data to decouple unreliable mechanisms from reliable ones.

Technology Policy and Research

As the practice of bridge assessment evolved, research efforts aimed at developing and identifying the role various technologies may serve within the realm of infrastructure assessment also ramped up. Although it is difficult to pin-point its origins, the confluence of new federal policies, the rising awareness of aging infrastructures as a key societal challenge, and a clear articulation of needed infrastructure research that occurred in the early 1990s all played a role. Following the fall of the Berlin Wall and the collapse of the Soviet Union, the U.S. Department of Defense began to recognize advantages of supporting the development of so-called dual-use technologies. The resulting policy sought to invest research funds into areas with broad applications, beyond defense, and resulted in significant funds being directed towards information technology, materials technology, electronics/sensing, and advanced simulation and modelling. Infrastructure assessment research benefited from this funding and also served as a compelling domain on which to base dual-use claims.

The focusing event came in September of 1993 with the tragic derailment of Amtrak's cross-country Sunset Limited on a bridge over the Big Canot Bayou near Mobile, Alabama. This derailment resulted in the death of 47 people (103 injured) and it remains the deadliest train accident in Amtrak history. The cause was traced to a track misalignment resulting from a barge impact eight minutes prior to the train crossing the bridge. Fueled by the burgeoning revolution in information technology, the prospect of a monitoring system that may have offered early warning caught the attention of many researchers, practitioners, and government officials. For example, following this event, the FHWA Advanced Research Office began to explore the feasibility of bridge monitoring to mitigate similar events.

Around the same time the U.S. National Science Foundation convened a Civil Infrastructure Task Group composed of multi-disciplinary experts with the goal of defining a research agenda for the renewal of the U.S. infrastructure. The resulting publication (NSF 1993) argues that infrastructures must necessarily be viewed from a systems perspective as opposed to the reductionist, component-level perspective. More specifically, the group recommended a series of strategic research directions, including (a) deterioration science (towards the development of a mechanistic understanding of deterioration and its causes), (b) assessment technologies (inclusive of nondestructive evaluation, long-term monitoring, and evaluation of remaining service life), and (c) renewal engineering (identification of effective preservation, repair, retrofit or renewal strategies). In the last two decades much progress has been made related to individual elements of this agenda, and while the systems perspective espoused by this task group remains unrealized, it is now almost universally recognized as a key barrier to effective infrastructure management.

Following these events in the early 1990s a dramatic increase in research activities related to technology-based infrastructure assessment occurred. A detail review of the literature is beyond the scope of this paper, but a brief chronology of a few key conferences and professional societies that were developed to disseminate and guide this research may be useful. Key examples include the biennial "Structural Materials Technology: An NDT Conference" held under the auspices of the FHWA since 1994 as well as the international NDT conferences starting from 1995 at Berlin (Schickert 1995). These conferences, as well as the Transportation Research Board meetings since late 1980's served to introduce new technology tools, as well as associated concepts and terms to bridge and transportation engineers. The Nondestructive Evaluation (NDE) Center was established by the Federal Highway Administration (FHWA) in 1998 in an effort to centralize and better coordinate research related to nondestructive testing. In addition, the International Structural Health Monitoring (IWSHM) Workshop which has taken place every two years at Stanford University since 1997 includes aerospace, space, automotive, defense and civil infrastructures applications of structural health monitoring for condition-based (instead of time-based) maintenance management. These workshops were instrumental in advances in space, aerospace and defense industry applications of the SHM concept. The SHM concept has also been applied to long-span bridges starting in Hong Kong since 2005 and an International Society for Health Monitoring Intelligent Infrastructures was established in 2003.

An especially important development during the 1990's relates to the formation of an American Society of Civil Engineers (ASCE) Structural Engineering Institute (SEI) Technical Committee named "Structural Identification (St-Id) of Constructed Systems," which brought together the leading multi-disciplinary experts in the world focusing on integrative approaches to characterizing actual constructed systems. Given that the interest in characterizing structures by field-calibrated models (by a systemic integration of analysis and experiment) emerged in the 1970's (Aktan 2013), it should be considered timely that this concept serves as a foundation for the next generation bridge condition assessment. The ASCE Committee published a book describing the "Approaches, Methods, and Technologies for Effective Practice of St-Id" (Catbas 2013). The writers have used the St-Id concept for bridge condition assessment and established an optimum approach to properly leveraging sensing, simulation, information and decision technologies for this purpose discussed in the following. The St-Id methodology for a systemic integration of analysis and experiment for bridge condition assessment are shown in Figure 1, indicating that a-priori modeling, experiment, model calibration and utilization are the fundamental steps of St-Id requiring a coordinated, integrative multi-disciplinary application together with the participation of bridge owners and maintenance engineers.

Integration of Technology

Given all of the investment into technology development since the early 1990s, it is interesting to consider why bridge assessments are carried out today in much the same manner as they have been for decades. One possible reason is that the integration both between the various technology development efforts and with the current practice has been missing. Although it is changing, researchers remain prone to pursue well-defined, highly technical development efforts in their areas of expertise. Such efforts are valuable, and they have led to the impressive sensing, simulation, and data processing/visualization tools now available. However, they are of limited use to the profession in this rather raw "unintegrated" form. For their part, practitioners have been engaged in the incremental adoption of such technologies, but this generally occurs in a piecemeal, ad hoc manner.

The missing piece to the puzzle is a broader effort that examines both the landscape of all relevant technologies to develop a hierarchy within the context of bridge assessment, inclusive of commonly observed performance problems. This requires more than simply adding the use of technologies into current practice in a few isolated areas based on specific problems. What is required is a systems approach that revisits both the criteria and constraints associated with bridge assessment in light of current and developing technologies, the characteristics of the work force, available funding, and our current understanding of bridge performance. The authors submit that the current incremental approach to technology adoption has not proven very effective, and thus a top-down restructuring of bridge assessment practice is proposed.

As a first step towards this larger effort, the authors have developed a potential approach to structuring various assessment technologies within the context of bridge assessment.

Technology Deployment Framework

Figure 2 below shows a proposed technology deployment framework. The central table of technology applications for bridge assessment is presented in increasing complexity and cost from left to right. In conjunction with this, one would expect a much more broad application (a larger number of bridges) for the technologies at the left side of the table, and a more narrow application for the technologies on the right half of the table (higher cost). This idea is implicit in current condition assessment practice, as we see load testing (a more expensive and in-depth activity) conducted on a very small subset of the bridges that are load rated analytically. As one might expect, SHM and St-Id tend to fall on the more expensive half of the table, and are almost exclusively applied on a bridge by bridge basis. Often, even in cases where there is a clear potential for appreciable return on investment, technology applications like SHM and St-Id are rejected due to “sticker shock.”

For technology deployment to be successful for transportation infrastructure, the industry must make a conscious effort to recognize and exploit the fact that investment into technology deployment on a single bridge must be leveraged not only to address the concerns with that specific bridge, but also to extract generic information to inform the management and assessment of the larger population. This feedback loop is critical, as it provides intrinsic value at the population level from otherwise cost-prohibitive technology deployments to small numbers of structures.

The technology deployment framework provides general guidance and examples of the types of technology applications that are relevant for transportation infrastructure. The framework is not an all-inclusive list of technology applications to be used in order as listed. Rather, it is a guide map that allows the user to choose both a destination and a route. Recall that a short-coming of visual inspection identified previously was that the inability for visual condition to reliably identify root causes of deterioration. In order to overcome this issue, the technology deployment framework should rely on the development of guiding questions or hypotheses (typically related to root causes or unexplained performances) which focus and constrain the application. Guiding questions provide context to help identify where and how technology can successfully be applied. Though the general progression would be left to right, increasing in both value and cost, the combination of technologies may vary greatly. It is useful and in fact essential to understand and then leverage the St-Id framework discussed earlier in any technology application as this framework is the best possible guide to formulating hypotheses and then validating or disproving these – essentially the scientific method of inquiry established by Aristotle who lived during 300 BC (Tredennick 1938). An excellent description of the scientific method of inquiry is offered by Wikipedia.

The last but perhaps the most important prerequisite for success in technology leveraging is to appreciate that the goal is not the generation of data and images but actionable information based on a clear and complete understanding of the bridge-foundation-soil and site system performance together with the root causes of any lack of performance. This requirement points to a need for bridge engineers with sufficient knowledge of technology as well as bridge behavior to design and coordinate integrated technology applications. A most common detractor of technology leveraging has been a lack of proper coordination, supervision and integration by bridge engineers for the extraction of actionable recommendations and knowledge as opposed to just data.

Conclusions and Recommendations

At the present time nearly 1 in four of the 609,438 bridges in the NBI fall into the structurally deficient and/or functionally obsolete category. In addition, more than 100,000 bridges are missing important information such as their as-built plans and foundations. The cost of correcting all of the bridge performance deficiencies with the current engineering and construction practice is estimated as $76 billion by ASCE's Report Card while current expenditures are estimated at half this amount. It is clear that we need to rethink our definitions for bridge performance and improve our assessment of bridge performance. This cannot happen by considering each bridge as different, and judging its performance based on the appearance of its elements while ignoring how the site, soil, foundations, substructures, bearings and the superstructures function as a complex system.

Recent research demonstrated that by considering their performance in terms of the mechanisms controlling demand and capacity, common bridges such as RC deck-on-steel girders or RC deck on precast PC box girders in fact perform as members of a statistical population (Catbas et al 2005). By leveraging design of experiments in conjunction with statistical sampling, it is possible to learn about the basic mechanisms of performance of an entire bridge population. This concept is now at the foundation of FHWA's Long Term Bridge Performance Program, which is expected to define and collect data on the performance of hundreds of bridges for decades.

Even when we leverage statistical sampling for studying bridge performance, there is a need for a framework to collect research quality data and information from a bridge. This cannot happen by just "field testing," but designing and executing any experiment by first clearly establishing the questions and hypotheses (possible answers) we wish to learn by the experiment, and then executing the experiment to validate or disprove the hypotheses. This is the scientific method of inquiry that is driving the space, deep ocean, and Hadron Collider research, and it should also drive any field experiment if we wish to extract not only data and information but also generic knowledge from the experiment. The St-Id framework has been shown to serve as a framework for designing and execution of field experiments in conjunction with the scientific method of inquiry and offers great benefits if it is adopted by bridge researchers who are engaged in field testing and NDE applications.

Finally, we need to emphasize the importance of a meaningful policy for selecting and integrating technology tools for field research and applications, especially if the goal in field applications is generic knowledge and not just data. Such a technology application hierarchy for bridge management is suggested in the paper, and this may serve as a draft for further discussion by the bridge engineering community.

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Figures

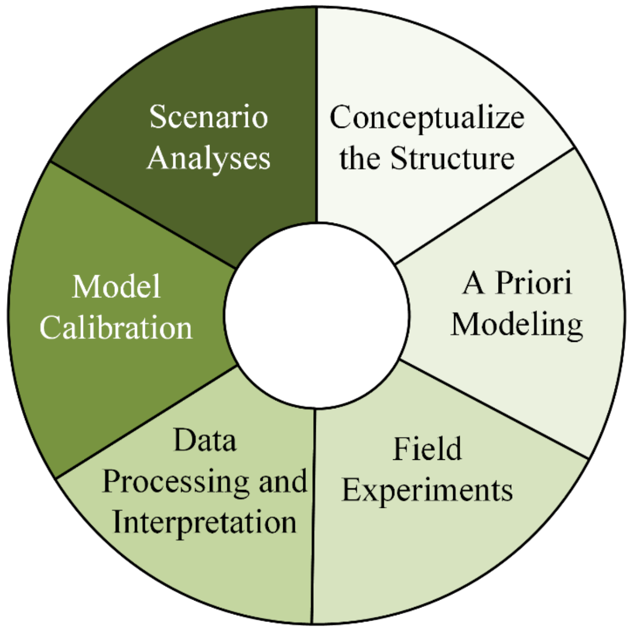
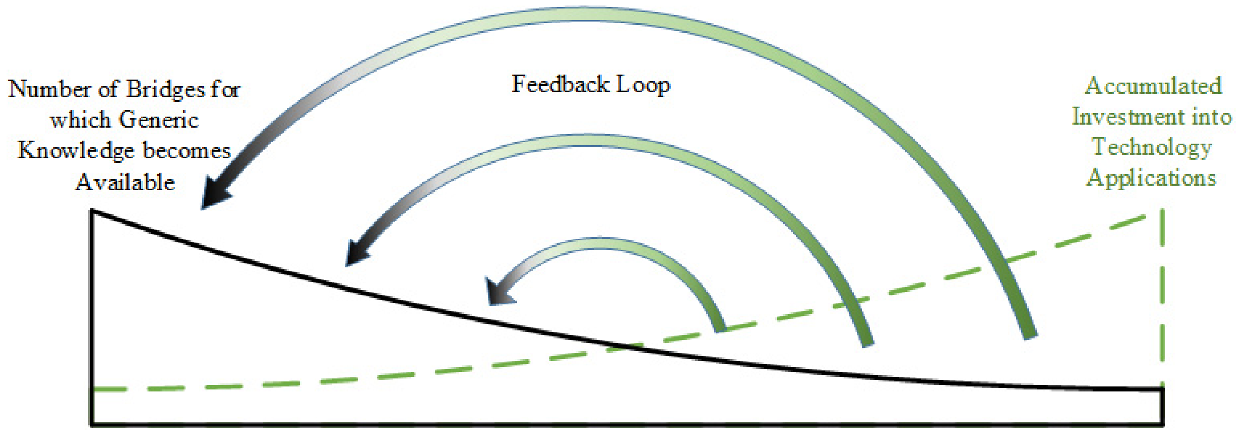


Figure 1 - Structural Identification



Technology Deployment Framework

High-Level Risk Assessment and Prioritization of Bridge Population	**Next-Generation Bridge Inspection and Performance Documentation**	**Quantitative Conceptualization of Geometry and Materials**	**Simulation, NDE, Short-term Structural Testing, and Model Calibration**	**Prognosis, Risk Assessment, Selection and Implementation of Corrective Actions**	**Operational Security and Structural Health Monitoring within Asset Management**
Ontology and database for bridge information system (BrIM)	In-depth Visual Inspection supported by novel access & imaging technologies	Surveying and GPS	FE Models and Simulation	Establish Demand and Capacity Envelopes	Traffic and weather data and images for operational safety
Rapid FE construction and analysis	Complementary Practical NDE	Non-contact Geometry Capture	NDE Assessment	Identification of Critical Hazards, Vulnerabilities & Failure Modes	Operational and Security Monitoring for Enforcement
Data mining for structuring bridges and performance concerns	Global assessment via rapid/practical vibration monitoring	Material Sampling and Testing	Load testing, short-term monitoring, and vibration testing	Scenario Analysis, Estimation of Cost of Failure to perform	Structural Performance and Health Monitoring (SPHM)
Design of Experiments approach to technology applications	Knowledge engineering and development of an information warehouse to archive heuristics	Development of 3D CAD leveraging BrIM System	FE Model Calibration to reduce uncertainty	Identification and Implementation of interventions & corrective actions	Specialized or Custom Inspections driven by SPHM

Figure 2 – Proposed Technology Framework