On Bridge Performance Monitoring for Risk-Based Asset Management

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Abstract
Ongoing research within the Long Term Bridge Performance Program, provides a unique opportunity to transform the state of bridge engineering. Large, long-term projects such as those undertaken by NASA for space exploration have shown the importance of planning and designing a research project involving significant epistemic uncertainty by first developing a foundation of scientific and intellectual construct. In this paper writers discuss an intellectual construct based on the concepts of lifecycle performance and its monitoring, risk, disutility, asset management, system identification and technology integration. It is shown that by leveraging these concepts, one may construct the foundations of a multi-decade and large-scale field research project that will promise potential for transforming how we engineer and manage our infrastructures in general and bridges in particular.

Keywords: Bridge Performance, Structural Identification, Performance and Health Monitoring, Risk-Based Asset Management

1. Introduction
The Federal Highway Administration (FHWA) Long Term Bridge Performance Program (LTBPP) was created by the Safe, Accountable, Flexible, and Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) for surface transportation in 2005. Funding continues for the LTBPP Program in the current legislation, Moving Ahead for Progress in the 21st Century Act (MAP-21). Partnerships with the States and AASHTO have been established to collect data from common bridges throughout the USA for decades. The principal driver for the LTBPP is to enable risk-based asset management of the Nation’s bridges (mandated by MAP-21) by collecting sufficiently long-term, objective, scientific quality data on design, construction and maintenance, as well as actual loads, behavior and performance from statistical samples of common bridge types. Initially data will be collected from the “RC Deck on Steel-Girders,” and “RC Deck on PC Girders” bridge types which comprise a large segment of the current NBI, but with many great regional variations in geometry, materials and design details. A considerable effort has been spent into the sampling process, accounting for climate, age, design specifications, construction practices, maintenance practices, truck loads and other parameters that may have a bearing on long-term performance. Clusters, corridors and reference bridges have been identified by stratified sampling. The fundamental research questions that are currently addressed by the program are: (1) How to objectively and completely define, measure, present and interpret bridge performance? (2) What legacy data, heuristic information, objective data and the associated metadata that should be collected in order to understand the performance of selected bridge types along with their most critical design, construction, operation, maintenance as well as region, site, organizational and network related parameters? (3) How to identify field test specimens by leveraging the design of experiments and statistics? How long, at what resolution and frequency should data be collected from the field specimens? What are researcher qualifications, additional training needs and the logistics of data collection that will assure the success and effectiveness of the program? (4) How can we take best advantage of IT, robotics and sensing, as well as modeling and simulation technology for facilitating data collection from the field? What are the minimum data management and quality assurance requirements?

The principal objectives of this paper include: (1) to suggest a conceptual framing of bridge
performance that the LTBPP is considering for the purposes of data collection; (2) to discuss the linkages between “Bridge Performance Metrics, Bridge Performance Monitoring, and Risk-Based Asset Management,” and (3) to offer a generic Performance and Health Monitoring (PHM) framework based on the System-Identification concept with associated technology integration recommendations to serve the needs of the LTBPP.

Given that the long-term goal of LTBPP is to enable risk-based asset management, we need to make sure that the PHM framework is aligned to enable risk-based asset management, with the goal of minimizing the risk that would correspond to any type of natural or manmade hazard that may lead to “bridge disutility.” A clear understanding of the intricate relationships between the concepts of “Bridge Performance; Monitoring Bridge Performance and Health; and, Managing the Risk of Bridge Disutility or Non-Performance”, are therefore essential for the success of LTBPP.

Currently, US bridge owners rely on the data in the National Bridge Inventory (NBI) which in 2014 included 610,749 bridges and culverts with a span length greater than 20 feet. These structures are assigned a Condition Rating between 0-9 during biannual inspections. A Condition Rating of 4 or lower, or posting of a bridge makes it structurally deficient. In the NBI 145,890 bridges (23.9% of the NBI) were indicated as structurally deficient or functionally obsolete. Furthermore, more than a half of the inventory corresponds to local bridges owned by Cities, Townships and Counties, of which 24% are structurally deficient or functionally obsolete, pointing to a disproportionate number of local bridges that are structurally deficient. As of 2014, over 10% of this nation’s bridges and culverts are posted for less than their legal load [1]. FHWA agrees that the current subjective inspection, condition and performance definitions based on NBI data is not sufficient and in fact can be misleading in the asset management of the highway transportation system.

It is important to assert that a most critical barrier to the success of LTBPP would be to assume that bridges maybe classified into superstructures, substructures and foundations. Even recognizing that a bridge “system” includes soil-foundation-sub-and-superstructures is not adequate; the authors suggest that bridges should be recognized as elements within a “Complex Socio-Technical System,” with many aspects of their behavior and performance that are not yet properly understood or known. We have to recognize and identify the relationships and interactions between the human, natural and engineered elements that actually govern bridge performance as critical infrastructure nodes, and how performance may change over a lifecycle given different limit-state demands and their return periods.

Writer’s goal is to make it obvious that meaningful research on bridge performance, bridge monitoring and risk-based asset management cannot be planned, designed and executed based on just current bridge engineering practice and by looking at bridges only through the lens of the design and evaluation codes and standards. Open and creative minds and the capability for field research as opposed to just field testing are necessary for success – just as in the case of Deep Ocean or Space research undertaken by NSF and NASA. Each bridge in the LTBPP has to be considered as a node point of a complex system-of-systems with cultural, organizational, societal and individual actors as critical variables in addition to the natural and engineered elements. A highway system delivers services – movement of freight and travelers – through various processes which are executed by actors, some more critical than others, and bridges are critical nodes of this system. Unless we recognize socio-economic issues such as history, culture, politics, policy, financing, revenue, state and federal contract laws and the human capital, we may be ignoring most critical variables that impact bridge performance.

2. Bridge Performance

Table 1 offers a broad overview of the performance of constructed systems in terms of limit-
states of performance, and the performance we expect should the demands that we design for at each limit-state are exceeded. The limit-states of performance incorporate demands from various elements of a bridge and the bridge-foundation-soil-site system as a whole with different return periods and probability of occurrence and exceedance. The Table also illustrates the relationship between asset management challenges for each of the limit-states, given different return periods, probability of demands exceeding capacity and performance expectations.

Table 1. Bridge Performance Limit-States, Return Periods and Expectations

<table>
<thead>
<tr>
<th>Infrastructure Life-Cycle Performance Management</th>
<th>Utility and Functionality Everyday</th>
<th>Serviceability and Durability 5-20 Years</th>
<th>Life Safety and Stability of Failure 50-750 Years</th>
<th>Resilience In the case of extremely rare catastrophic events 2500-5000 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asset Management</td>
<td>Operational Management</td>
<td>Maintenance Management</td>
<td>Multi-hazard Risk Reduction and Management</td>
<td>Disastrous Response Planning and Emergency Management</td>
</tr>
<tr>
<td>Performance Criteria</td>
<td>Minimize Disruptions Maximize Reliability</td>
<td>Effective &amp; Economical Inspection Maintenance Repair Rehabilitation Assurance of Life Safety Control of Failure Mode Reparable Damage</td>
<td>Quick recovery of normal operations following any hazard (days-months)</td>
<td></td>
</tr>
<tr>
<td>Starting at Design &amp; Throughout entire lifecycle</td>
<td>Minimize Casualties and Sustain an Acceptable Level of Function for: Society, Economy, Ecology, Government and Critical Infrastructures</td>
<td></td>
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<td>- Relative importance for Network, GDP, National Security, etc.</td>
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<td>- Operational efficiency, safety and Security</td>
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<tr>
<td>- Robust and predictable revenue</td>
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<tr>
<td>- Resourceful and Adaptive Society, Economy, Public Health and Emergency Response</td>
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<tr>
<td>- Recommending the use of flexible, integrated life cycle management strategies</td>
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<td>- Protects escape and evacuation capacity</td>
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<td>- Non-fragility of Interdependent Infrastructures</td>
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We expect maximum demands for the utility, functionality and serviceability limit-states may occur once-every-Five years throughout the lifecycle of a bridge. The demands that may drive a bridge into the life-safety, stability of failure and resilience limit-states are associated with much greater return periods (50-5,000 Years) and are associated with significantly increasing uncertainty. A bridge may never be driven to these advanced limit state demands throughout its lifecycle, and its performance would then be governed by utility, serviceability and durability. However, bridge owners and consulting engineers cannot count on a bridge and its approaches not experiencing any hazards or accidents and should remain responsible for its performance under advanced limit state events. Further, we expect bridges to perform at a design level of service and not require major maintenance such as deck resurfacing and overlaying for at least 20 years. Meanwhile, anecdotal evidence points to many new bridges not delivering such a serviceability and durability performance. We may hypothesize many reasons for this, which the LT-BPP is expected to identify by scientific research.

The probability of not performing and the consequences of not performing often increase as a bridge is driven to higher limit-state demands. For this reason, when bridge conditions are evaluated, it is critical to appraise the probability of hazards that may impact life-safety performance and the likely failure modes. This requires an accounting of the network functions of the bridge as well as the site, climate, hydrology, geography, geology and soil-foundation conditions that may impact performance during a hazard.

More detailed discussions on bridge performance have been offered elsewhere [2], however, the above discussion should be sufficient to indicate why PHM of a bridge requires a careful
performance evaluation given clear, quantitative and objective criteria for performance at every limit-state. In addition, performance requires an engineer to be capable of envisioning all probable critical demands and the corresponding bridge performance throughout its lifecycle. A lack of clear and objective definitions and quantification of performance at different limit-states makes this difficult, and the LTBP is expected to rectify this need. **Data collection on bridges that fail to perform and on those that have successfully performed during their lifecycle will be especially critical to quantify performance in terms of probability of not performing or disutility under a variety of bridge attributes and demands.**

### 3. Asset Management

Asset Management (AM) paradigm has its origins in operations research, a discipline that deals with the application of advanced analytical methods to help make better decisions. If properly leveraged, AM may enable performance-and-risk based, transparent and effective stewardship of large and complex socio-technical systems. In the context of infrastructure systems such as transportation, water, power, energy and communication, which are all in the realm of complex socio-technical systems, AM may provide information about the trade-offs associated with decisions involving policy, organization, operations, services, products, asset preservation, revenue, financing and capital investments. By providing decision options to infrastructure managers so that they may optimally reconcile conflicting objectives and constraints, it may be possible to make local and regional management decisions to optimize system performance rather than investing into maintenance, rehabilitation and renewal of individual elements or corridors without considering their interactions and interdependencies.

We note that in the US AM has been advocated by the US GAO (e.g. GAO-08-763T, GAO-13-402T), and encouraged by the US EPA [3] and USDOT FHWA [4] as oversight agencies for the water and highway transportation systems since the early 1990’s. MAP-21 [5] required States to develop a risk- and performance-based asset management plan for the National Highway System to improve or preserve asset condition and system performance; plan development process must be reviewed and recertified at least every four years. One shortcoming that reduces the favorable impacts of MAP-21 is a lack of objective metrics to describe condition and safety of assets. For example, currently, condition rating of bridge decks based on visual inspection is considered as a basis for judging a State’s performance. The crux of a contemporary and systemic application of infrastructure asset management is to be able to define, measure and monitor the performance of the system in terms of explicit, measurable indices, and also to be able to establish the contributions of each asset to the lifecycle benefit/cost of the entire system. This is currently difficult for many civil infrastructure systems as we lack standards for asset evaluation, asset condition assessment and asset contributions to system lifecycle benefit/cost [6]. In New Zealand, NAMS (http://www.nams.org.nz/) issues an International Infrastructure Management Manual [7] which is considered as a model by many infrastructure agencies in the Far East, Europe and North America. According to NAMS, an infrastructure AM plan should incorporate the following principles to be effective:

- **Taking a lifecycle approach**
- **Developing cost-effective management strategies for the long-term**
- **Providing a defined level of service and monitoring performance**
- **Understanding and meeting the impact of growth through demand management and infrastructure investment**
- **Managing risks associated with asset failures**
- **Sustainable use of physical resources**
- **Continuous improvement in asset management practices**
The challenge in front of the LTPP is to work with the FHWA Asset Management Office in expanding on the above NAMS AM principles and formulate data, information and knowledge that is essential for managing bridges as elements within the highway system. This will require a careful evaluation of policy (or lack of) and traditions of various State DOT’s to understand how these organizations have evolved, and whether they have established sound principles in how they oversee the design, operation, condition evaluation, maintenance and repair or renewal of their assets. It is important to note the distinctions and differences between the asset inventories, human resources and organizational effectiveness of different State DOT’s. However, one may hypothesize an **iterative AM approach** that may be based on collecting objective data and continuously improving how assets, asset conditions and performances are evaluated. Further, AM is not just about maintenance and repair but should include the entire set of performance limit states. Various modules that would be included in an AM program for a bridge (or a population of bridges) and leveraging IT capabilities that are currently available may be envisioned as shown in Fig. 2.

**Figure 1. Schematic for Asset Management Modules**

The AM schematic in Fig. 1 leverages a Central Information Repository where all legacy data and information from design, construction and operation as well as inspection reports and correspondence are preserved in an electronic and searchable archive, supported by visualization tools labeled BrIM which would offer integrated 3D CAD and corresponding images. The Central Information repository can be accessed between various organizational units in real-time. These are outlined at the right side of the figure. An important module envisioned for a contemporary AM capability – at least for large/major/long-span/highly critical bridges would be a “Performance and Health Monitoring System (PHMS)”. This system may be developed as an extension of the roadway traffic monitoring and/or security systems and will provide measurements and real-time display of weather and ambient conditions, truck load information, critical bridge strains, accelerations, tilts and deformations and possibly even bearing reactions. Current sensing and wireless communication technology offer great potential for such an envisioned remote and real-time monitoring of critical bridges for leveraging objective data and images for operations, safety, security, inspections and maintenance management decisions. The challenge is in translating the data and information about past and current bridge conditions, performance and health into risk of disutility or non-performance at any one of the critical limit-states discussed in relation to Table 1.
4. Risk-Based Asset Management

A challenge faced by bridge owners is to be able to assess the risk of a lack of performance or disutility of a given bridge. The following figure (Fig. 2) provides an overview of disutility risk and the hazards that lead to risk, illustrating the complexity of evaluating disutility risk of a bridge as a product of the likelihood of Hazards, Vulnerability and Exposure, which are the critical concepts in defining and evaluating risk.

One of critical considerations in any risk evaluation method is a conceptual understanding of the probabilistic nature of hazards that may correspond to different limit-states and the different nature of uncertainty that may be associated with different hazards.

![Figure 2. (a) Evaluation of Infrastructure Disutility Risk; (b) Hazard Classifications for Risk](image)

Fig. 3(a) illustrates how hazards may fall into Neon Swan, Random and Black Swan type events based on the prevailing nature of uncertainty (Neon swan events are statistical but may be characterized as nearly Deterministic with respect to their mean; Random events are based on an estimated histogram or Probability Distribution and Black Swan events are driven by Epistemic Uncertainty, based on a complete lack of previous experience). Obviously, different financial and organizational strategies for mitigation and investment considerations are needed for different hazards based on their associated uncertainty, return period and consequences. It is also important to note that it is always desired to avoid risk by avoiding the “Neon-Swan” type of hazards by proper management and investment than face the consequences after such hazards actually take place.

To further this discussion on risk-based asset management, it would be desirable to take the concepts discussed in relation to Figures 2-3, and demonstrate specific quantitative applications to different bridges governed by different hazard environments at different regions of the country. Given that LTBPP will have access to virtually every State DOT and their inventory, it is natural for this program to demonstrate how to evaluate disutility risk for a bridge and how risk may vary between states given their differences in inventory, hazards, cultural and organizational attributes. Correlation of the estimated risks by leveraging data
from bridges that actually have failed to perform will be transformative, as current bridge design assumes a uniform reliability with a safety index of 3.5.

Figure 3. (a) Different Nature of Uncertainty Governing Various Hazards; (b) Relations between Return Period of a Hazard, Consequences of Disutility and Probability of Disutility

5. Bridge Performance Monitoring for Risk-Based Asset Management

The LTBP Program is interested in a framework for Performance and Health Monitoring (PHM) of bridges both for serving the data and information needs of the research program necessary for the selected “reference” bridges. This framework is NOT a protocol or users guide but an intellectual construct that will drive any protocols and applications. However, a framework may also support the State DOT’s and other bridge owners for leveraging the concept of PHM prudently given the widely accessible and abundant sensing, imaging and communication technology. One goal of this paper is to offer context for bridge PHM – also called bridge structural health monitoring SHM, and how such an effort should be viewed as an integral part of a risk-based asset management strategy.

We note that PHM or SHM involve much more than sensing, imaging and communication, irrespective of whether data and images are communicated in real-time or at intervals of every other year. We need to be clear about the scenarios which may justify an investment into PHM or SHM and the circumstances under which SHM would offer much greater insight than an inspection by an experienced bridge engineer.

We need to assert that SHM is NOT placing sensors and collecting data as most vendors assume. SHM should have a clear purpose, such as identifying the root cause of a performance deficiency and/or the time a bridge may require intervention due to disutility. For example, many State DOT engineers ask if SHM can help in the case of bridges that exhibit performance deficiencies such as a “bump” as trucks enter a bridge. A bump may be caused by the erosion of fill under an approach slab often due to inadequate drainage, and this can only be identified by proper observation and heuristics. However, if a bump is being caused by rigid-body rotation of an abutment, a joint or a bearing failure, SHM may prove useful for pinpointing these causes and help point to effective remedies.

Before we discuss SHM further we need to state some basic principles and prerequisites:

- A convincing business case based on AM needs – given that a proper SHM installation and data interpretation from a bridge is an expensive process requiring so much expertise that it can be trusted only to a handful of entities at this point in time.
- Understanding that the network a bridge is serving, its approaches, superstructures, substructures, foundations and the site characteristics (climate, weather, geography, hydrology, geology and the soil) as well as the organizational characteristics of the owner-agency make up a complex and coupled socio-technical system. Although we have greatly
fragmented our engineering practice and research on bridges, SHM cannot succeed without a holistic systems approach treating a bridge as a “patient”.

- Bridge SHM has to recognize that bridge performance and health should be defined within the entire lifecycle and including the limit-states of Utility and Functionality; Serviceability and Durability; and, Safety, Stability of Failure Mode and Resilience. These limit-states relate to demands that may take place and recur from several years to several thousand years. Irrespective of the current age and expected lifecycle of a bridge, its SHM should be designed by recognizing all of the risks due the bridge not performing as expected under the maximum demands at any of these limit-states. In other terms, SHM should not focus on a minor crack while being oblivious to the patient having terminal cancer.

- The principal mechanisms that impact the load effects and responses of the bridge and all the critical elements of the bridge system have to be understood and incorporated in a field-calibrated FE model – at a resolution and with confidence in predictions that should be justified by the business case for SHM. The process of developing a field-calibrated model of a bridge system is called structural identification, further described in the following.

- Once a bridge system is identified and its performance deficiencies and/or risk of not performing are estimated, its SHM may be designed based on the business case driving SHM. This process requires an integration of bridge management, bridge engineering heuristics and technology leveraging. There is no equal value to an experienced bridge engineer visiting and evaluating a bridge, noting its performance deficiencies and risks of not performing at critical limit-states of safety, integrity and resilience. Technology leveraging will reinforce and quantify the intuition of an experienced bridge engineer but cannot be of much value without such heuristics.

6. Structural Identification, PHM or SHM application framework

Figure 4 below outlines the structural identification process where each step should be carried out from 1-6 in proper order, then repeated as many times as necessary in an iterative manner [8]. PHM or SHM may follow, should there be a business case, and may even be envisioned as a continuous or intermittent application of Steps 3-6.

![Figure 4. Six steps of Structural Identification](image)

**STEP 1.** Clearly establishing a business case, in conjunction with the drivers and specific
objectives for a St-Id application and identifying any critical organizational, technical or resource-related constraints that may challenge its success.

Collect and evaluate all available legacy data and information including heuristic knowledge about the constructed system. Construct a digital warehouse that will serve as a library for all the legacy and new material. Given the recent advances in information modeling (BrIM) and bridge management systems (BMS), they may be integrated and leveraged to serve as a library. This need was discussed in relation to AM earlier.

Given that very few owners, consulting engineers and even large consulting companies may claim successful experiences with technology selection and integration, it is both a challenge and also a prerequisite to convince an owner and the owner’s consulting engineers’ to understand and support the need for St-Id and SHM of a constructed system. It is therefore critical to understand the owners and consultants concerns and the relationship between owners and their consultants. Some owners may prefer to delegate all professional engineering work to consultants, and a St-Id application will often have to be approved and supported by the consultant who may be in charge of the inspection, maintenance, repair or management of a facility.

Scenario’s that may justify a business case for BHM or SHM of an existing bridge or a statistical sample of a bridge population may include: (a) AM of long-span or complex (moveable) unique bridges that are critical for safety, economy and other reasons for a region or network; (b) important bridges that have reached the end of their service life – either due to design or condition – but cannot be renewed in a timely manner; (c) research for: improving our understanding of bridge performance and factors that impact bridge lifecycle performance - such as the LTBP program; to calibrate current design and evaluation standards; to advance the state-of-the-art in technology leveraging; ensure the safety of new designs and construction methods, etc.; (d) understanding the root causes of performance deficiencies due to complex behaviors such as excessive vibration, unexpected movements, settlements, freezing of movement systems, material or joint failures such as cracking, spalls, chemical reaction, slippages, unusual corrosion, fatigue, etc. Some of these performance deficiencies may be traced to design errors, others to a combination of causes - weather, inexperience, lack of quality control, lack of proper curing, early loading, etc. - during construction, operation, inspection and maintenance. Without structural identification and monitoring, it may not be possible to clearly identify and separate the coupling between root cause(s) of performance deficiencies and design effective interventions to mitigate them.

In general, infrastructure owners may be motivated to leverage St-Id and SHM if an application promises to save a portion of repair, retrofit or renewal funds or at least ascertain the effectiveness of renewal designed in a traditional code-based approach. A challenge to SHM may be that many consultants tend to see a constructed system through the lens of prevailing design codes, and may not recognize how different the actual behavior may be and therefore the value offered by St-Id. Given that codes for new design aim to simplify complex interactions and are often blind to how structural-foundation-soil systems actually perform, many renewal applications are designed to make a deteriorated system to look like the original design. However, such renewal designs with complex and difficult constraints such as staging and continued operations may not be effective, and may be even unnecessary. A mechanistic understanding of an existing constructed system and its characterization by a calibrated analytical model, and in some cases even a scaled physical model may prove critical for assessing retrofit strategy and implementation.

Still another compelling business case for St-Id may be to establish a quantitative and mechanistic baseline characterization for a newly constructed system – in terms of flexibility/stiffness, force distribution mechanisms, kinematics and damping. Such a characterization is invaluable in the case of performance-based engineering, a paradigm that is
expected to become critical especially with PPP financing of infrastructures. In each case, a strong business case is required before convincing an owner and/or an owner’s consultant regarding the expected payoff from St-Id.

**STEP 2.** Following a study of legacy data and information, it is necessary for an experienced technology integration coordinator for St-Id, SHM, BPM and/or AM to observe and measure the system in the field under different operational and environmental loading conditions. The system and its inputs as well its mechanisms for load transfer along with any sources of uncertainty need to be conceptualized for a-priori modeling. One should take advantage of practical measurements during field observations for capturing as-is dimensions, material properties and global structural characteristics such as natural frequencies and mode shapes. This is arguably the most consequential step requiring an ability to observe an actual full-scale system in the field, leveraging heuristics, and identify the characteristics, loading and response mechanisms – i.e. site, soil, foundation; load paths; displacement, deformation and any concentrated distortion patterns; boundary, continuity and movement systems - that should be incorporated in the a-priori model. Field observation offers the opportunity of reducing uncertainty about operational response levels, and any condition and performance deficiencies that should be recognized in modeling. A virtual reconstruction in 3D CAD is a most useful effort for a correct modeling of the geometry, noting that in many cases 2D plans may contain inconsistencies and what may appear as insignificant idealizations in geometry may lead to significant discrepancies in simulated and measured responses.

When justified based on the business case for SHM, we envision this step to begin with a comprehensive visual inspection by a qualified structural engineer while various technology tools are leveraged in parallel with the inspection. The entire step and in fact the entire St-Id application would greatly benefit from leveraging BrIM in conjunction with 3D CAD and visualization tools. Non-contact measurement technology such as Photogrammetric or 3D Laser Scanning approaches may be used for the 3D CAD, material sampling and testing for characterizing material properties and their distributions and measuring accelerations at strategic coordinates of the structure may help to estimate its global dynamic characteristics – frequencies and mode shapes. Also recommended is to observe how a system and its loading environment may change with time over the short-term (hours - months). All of this information should be transferred to a 3D finite element model of the entire system, inclusive of foundation and soil.

In the construction of an a-priori model it is important to recognize that an infinite number of models can represent a system. **The model-builder has to have experience with constructed systems, as FE software will permit the construction of various models that may appear to simulate the geometry with fine resolution but still fall short of simulating the kinetics and kinematics. It is highly recommended to construct a model that can serve the objectives of St-Id at a minimum necessary resolution.** In general, mixed microscopic and element level models, which represent critical details and regions in microscopic detail but represent less critical elements at an element level and in some cases even smearing several structural elements into one analytical element may be a meaningful approach. There are a number of best practices recommended for FE modeling by experts in this field, and some examples may be found in the ASCE Committee Report [8]. However, the single most critical practice is calibrating the software, its FE library, the hardware and an understanding of these by analyzing several benchmark problems. It is also advised to leverage two different software packages, and follow stringent processes for identifying human errors in transferring geometry, materials, continuity and boundary conditions to the model. Human errors are inevitable, and data collected to reveal the global frequencies and mode shapes will be invaluable for ascertaining that the model is at least simulating these global properties.
STEP 3. This step is often the most expensive since it often requires interventions to the operations of the constructed system. Field experiments require highly specialized engineers experienced in getting close access to structural members and connections, sensors, electronics and IT in addition to being excellent structural engineers. A field experiment should be planned, rehearsed, and executed with imaginably the most stringent standards, requiring its own heuristics. However, it is most important to note that the three Steps discussed so far have to be considered and executed as a continuum, with the same coordinator and preferably the same team.

There are several types of field experiments including: (a) ambient vibration testing, (b) forced excitation testing, (c) controlled load testing, and (d) monitoring operational and environmental events, with an St-ld campaign including one or more of these components with (a) or (b) more likely to be first, and (d) to run to the end. Application of (c) is already a requirement of a number of transportation agencies worldwide.

The a-priori model should be leveraged to design each type of experiment and especially the instrumentation requirements by identifying the force-paths, transfer mechanisms, critical members and details for measurements together with the bandwidth, range and gage-length of each sensor. There is a fine balance between the a-priori model and the type and density of data recommended for each of the experiments. Instrumentation should be designed to: (a) control the safe and successful execution of the experiment; (b) test hypotheses regarding critical structural behaviors and the root causes of any condition issues; (c) immediately assure data quality and that any critical data is not being missed; (d) serve as the basis for the model refinement and calibration step.

The information provided by various experiments in (a) to (d) above complements each other: Ambient vibration monitoring over a day to weeks provides average values and variations in the operating strains, deformations, tilts and accelerations. Frequencies, mode shapes and damping of various modes may be extracted. Monitoring operational and environmental events over several weeks to several months provide average magnitudes and bounds of inputs and responses due to not just live loads, but also wind, temperature and gradients, radiation and other intrinsic force mechanisms.

A controlled load testing (c) performed during steady temperatures, in conjunction with a sufficiently dense, multi-modal sensor array measuring critical displacements, tilts, deformations and strains under various stationary and moving load patterns provide the best, most definitive path to calibrating and validating a FE model. Such an exercise can be performed within hours given an adequate sensor array. The prerequisite is to ensure the safety of the structure during proof-level loads. How to perform proof-load testing safely especially when bridges have unknown properties and missing documentation has been discussed in a FHWA Tech Brief by the writers [9].

STEP 4. The activities in this Step should occur to some extent in ‘real-time’ during the St-ld experiment or monitoring. It is critical to have situational awareness during a load test and identify, in near real-time, any nonlinearity, a shifting of load path, and any malfunctions that may lead to data loss. Following the experimental campaign, the step continues in the data visualization and interpretation laboratory.

This category requires an excellent computational engineering and IT background. Metadata and data need to be checked for quality assurance and archived prior to processing, preferably during the experiment, to catch and rectify mistakes in-situ. Real-time checking and subsequent processing of dynamic and static data for extracting the mechanical properties of a system and patterns require a good signal processing background. Technology advances in SHM facilitate on-site analysis of dynamic data that can advise changes in experimental strategy in near real-time.
**STEP 5.** Irrespective of any other (data-based) model that may be extracted from data, calibration and validation of a physics-based (often mixed, smeared-element level-microscopic FE) model for scenario analysis and decision-making is essential for using St-Id (and the repetition or continuous applications of Steps 3 and 4 for BPM or SHM) as a tool for addressing structural engineering problems. An argument by scientists researching St-Id for mechanical systems has been: How can we justify a linear physics-based deterministic model when a structure may be nonlinear, non-observable and non-stationary as all constructed systems are at various degrees? This argument stems from the different mind-models of a structural engineer and an applied math – or – a theoretical and applied mechanics expert. The structural engineer is well aware that a constructed system cannot be strictly linear and in fact will have many localized nonlinearities. Further, a constructed system is never entirely observable or stationary, and many critical parameters and mechanisms are clouded by not only random but epistemic uncertainty [10].

The real challenge in the St-Id of constructed systems - and what makes this an art - is to anticipate whether it is appropriate and then rationally smear all the nonlinearity and non-stationary characteristics of a system into a linearized, physics-based model that is suitable for the objectives of the St-Id application. Naturally, one has to remain skeptical of a model until it may be validated as complete, and proven suitable given the objectives of St-Id. Depending on the objectives of St-Id, and the consequences of the uncertainty in over-or-underestimation of the demands, capacity and vulnerability, and all of the critical failure modes of a structure-foundation-soil system, the size, resolution and sophistication of a physics-based model would change. This model can never be unique, and in some cases it may be necessary to incorporate local nonlinearity. However, as long as a reasonable amount of reliable data on global and critical local behaviors are acquired and physically interpreted, it should be possible to leverage heuristics and reach a reasonable level of confidence in a model as one that represents important characteristics of the actual constructed system.

**STEP 6.** This Step concludes one full cycle of a St-Id and SHM application to a constructed system. As discussed earlier, Steps 1-5 need to be coordinated and carried out by an expert team of structural engineers experienced in infrastructure management, computation, IT, modeling and simulation, experimental arts, signal processing, and perhaps most importantly all relevant heuristic domain knowledge regarding a specific constructed system, soil and materials. The St-Id team is expected to leverage a wide spectrum of technology in an integrative manner. A full cycle of a journey along the six steps should not only produce data or simulation models, but considerable insights regarding the operations, loading environment, performance, condition and reliability of the structure and of the risks associated with any lack of performance of the system at any critical performance limit-state.

Step 6 involves leveraging the calibrated model for prioritizing risks of the system not performing, scenario analyses, evaluating and making decisions regarding the performance and/or condition concerns, and/or retrofit and renewal design. Whether it is a principal driver or not, one should expect that any critical risks due to probable non-performance or disutility of the system at any of the functionality, utility, serviceability, durability, safety and stability of failure limit-states should be an outcome. Critical hazards, vulnerabilities and probable failure modes need to be identified, validated and documented as an objective overview of the health of a system, in addition to any other objective in order to strengthen the business case for St-Id.
7. PHM Following Structural Identification

There have been only a few success stories where bridge structural identification or performance and health monitoring efforts have been successfully implemented to address actual performance concerns even though SHM has been advocated for more than two decades. We note that successful applications require the coordination of the entire process – i.e. all Six Steps - by the same expert – who should be an engineer/manager with a sound understanding of both heuristics as well as the technical challenges of each of the six St-Id steps. Such a project manager should be: (a) experienced in systems integration, as the essence of St-Id and SHM are to integrate the experiment and analysis to provide insight to owner/operator, consulting engineer, (b) an expert in modeling (integrating analytical, mathematical, numerical and computational modeling), (c) an expert in experiment who can design and execute field experiments to capture the critical behaviors of an actual operating constructed system, (d) an expert in risk, reliability and uncertainty analysis and optimization - who can judge the reliability of analysis and experiment while correlating the two, and finally; (e) an expert manager who can integrate the empirical-heuristic knowledge with the objective-mechanistic insight provided by St-Id and articulate this to owners for making prudent management decisions.

Table 2 provides how the Six Steps of St-Id and SHM/PHM are related and have to be designed, developed and implemented in concert. Table 2 also lists technology tools that may be integrated for a streamlined application of PHM for bridge asset management.

Table 2. Structural Identification and PHM Steps vs Technology needs

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<td>In-depth Visual Inspection using high-fidelity devices to ensure comprehensive, photographic and descriptive documentation</td>
<td>Development of FEM models and simulations to identify critical sections, members, connections, and associated failure modes</td>
<td>Establish Critical Demand and Capacity Envelopes and obtain reliability curves and capacity rating</td>
<td>Identification of Critical Hazards that may modify the inherent deficiencies of the structure</td>
<td>Operational Enhancements including variable lanes and speed to estimate traffic systems for safety, open-road testing, etc.</td>
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<td>Practical NDE as needed to enhance and validate visual inspection</td>
<td>Non-Contact Geometry Capture (photogrammetry, laser scanning) to obtain higher resolution and more precise geometric representation of complex regions</td>
<td>Controlled Load Testing: either Diagnostic or Proving Load to establish force-resisting connections and load paths</td>
<td>Scenario analysis and Risk Assessment to identify and rank the most critical risks</td>
<td>Automated Operational Monitoring and Law Enforcement including speed and lane change monitoring, weigh-in-motion, license plate ID, auto flagging enforcement, etc.</td>
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<td>Knowledge Engineering informed by interviews with experienced operators to capture relationships</td>
<td>Material Sampling and Testing to fully characterize test materials related to their mechanical properties (strength, stiffness), chemical composition, microstructure, etc.</td>
<td>Short-Term Monitoring of live load and temperature induced responses to characterize leading environment</td>
<td>Estimate the Cost of a Failure and to perform risk analysis, potential loss of human life, direct costs, time costs, economic impact, etc.</td>
<td>Security Monitoring including comprehensive surveillance, video analytics, weigh-in-motion, explosive-safing sensors, etc.</td>
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<td>Development of an Information Warehouse complete with a schematic from historical records, material, legacy data and documentation for method</td>
<td>Development of PHM to fully incorporate the structural form and to serve as the interface with the information and knowledge for an FEM model</td>
<td>Forced-Vibration Testing and modal analysis to capture global dynamic properties and nodal flexibility</td>
<td>Identification of Appropriate Actions that may consist of risk mitigation through minor or hazardous situations, e.g. (towering, missing, or “no nothing”)</td>
<td>Structural Health Monitoring to track critical parameters, real-time image/video, automated comparison with baseline models, real-time rating, automated reporting, etc.</td>
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<td>Ambient Vibration Testing to capture operating global nodal parameters</td>
<td>Calibration of FE Models by recalculating measured and simulated responses through modification of uncertain aspects</td>
<td>Implementation of Corrective Action monitored to validate design, staging, and to provide baseline response for future performance assessment</td>
<td>Special and Custom Inspections based on SHM – Lifecycle Consulting / Risk Management</td>
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8. Conclusions

Bridge performance and health monitoring (for brevity, PHM or SHM) is a paradigm that requires a careful justification, planning, design and implementation process. Just as a primary-care doctor has to perform a comprehensive physical and mental health evaluation of a patient
and establish a baseline for monitoring his health, we need to evaluate the performance of a bridge by its structural identification before we may decide on what aspect of health should be monitored. Along this reasoning, just as the resources available to a patient and family circumstances would be critical in a health evaluation, one has to include an evaluation of the organizational aspects of the owner-agency before justifying PHM. Unfortunately, many existing applications have been designed without a clear business case and without clarifying the questions that need answers from a PHM application.

Some aerospace engineers and technicians who may not understand the scale, lifecycle and uncertainty in the properties and the demands that should be expected in evaluating the health of a bridge propose to install sensors and monitor responses indefinitely before establishing what is normal. This is highly dangerous because where, what and how to sense inputs and responses of a bridge for SHM depend on a complete understanding of the loading and response mechanisms. Until we accumulate sufficient knowledge on these mechanisms through the LTBP program, SHM applications should be trusted to those who may properly integrate heuristics and technology tools. We may envision SHM as neurosurgery of a patient applied in the field – where there can be success only if every step is carried out successfully and with due prudence and diligence. Current civil or mechanical engineering practice is not yet ready to quickly learn, train and apply SHM especially to large numbers of bridges for research purposes. We recommend caution and careful planning and selection of appropriate teams, their coordinators and their quality assurance overseers.

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References