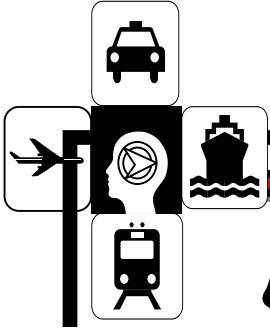


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Tech Brief

BRIDGE APPURTENANCES PART A: ENERGY ABSORBING FENDER SYSTEMS PART B: PRE-CAST OR PREFABRICATED BRIDGE DECK SYSTEMS PART C: SMART BRIDGES

FHWA-NJ-2003-011

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SUMMARY

This technical brief presents the findings for the NJDOT's technology transfer projects, **Energy Absorbing Fender Systems**, **Pre-Cast or Prefabricated Bridge Deck Systems**, and **Smart Bridges**, research problem statement numbers, respectively, 2001-05, 2001-06, and 2001-07. This research project was initiated by the New Jersey Department of Transportation and commissioned to City University of New York Institute for Transportation Systems. *Prof. N. Parker* of The City College of the City University of New York was the Principal Investigator, and *Prof. F. Ansari* of University of Illinois at Chicago was Co-Principal Investigator. They were assisted by *Prof. M. Ghosn* and *Prof. K. Subramaniam* of The City College, and graduate students *S.J.M. Meja* and *B. Quinlan* of The City College and University of Illinois at Chicago, respectively.

Part A: Energy Absorbing Fender Systems

A literature search indicated that the current practice for the design of bridge pier protective systems is based on energy considerations. The kinetic energy of the vessel just before impact is transformed into an equal amount of energy that must be absorbed by the protective system through deformation. The existing technology which has been used for bridge fender protective systems by other states or countries was identified and grouped into six main categories: 1) Pile supported; 2) Retractable; 3) Rubber; 4) Gravity; 5) Hydraulic/pneumatic; and 6) Floating systems.

A protection system composed of **HARDCORE COMPOSITE PILE DOLPHINS, COMPOSITE TUBULAR PILES WITH STAY-IN-PLACE FORMWORK SURROUNDED BY COMPOSITE ULTRA HIGH MOLECULAR WEIGHT FACED FENDER PANELS** was recommended as the state-of-the art system for New Jersey Department of Transportation. This recommendation was developed by rating six generic design alternatives based on their life cycle cost over 40 years.

Part B: Pre-Cast or Prefabricated Bridge Deck Systems

Two categories of pre-cast bridge decks were studied to determine their prevalence, performance, cost efficiency, and construction methods. The first category was the pre-cast superstructures (box beams, tee-beams and pre-cast segmental components). The second category was the pre-cast bridge panel (partial or full depth). It was found that more than 50% of bridges built in the United States are classified as pre-stressed concrete structures.

THE STUDY CONCLUDED THAT PRECAST BRIDGE DECKS HAVE SEVERAL ADVANTAGES OVER THOSE THAT ARE CAST-IN-PLACE INCLUDING FASTER CONSTRUCTION SCHEDULES, LONGER SERVICES LIVES, AND POTENTIALLY GREATER COST EFFICIENCY. THE USE OF PRECAST BRIDGE DECKS IN CONJUNCTION WITH NEW CONSTRUCTION MATERIALS SUCH AS HIGH PERFORMANCE CONCRETE AND FIBER REINFORCED COMPOSITES WAS RECOMMENDED.

Part C: Smart Bridges

Smart bridges utilize different instruments to monitor various physical parameters under different weather and loading conditions. Listed below are five of the most important parameters of concern to engineers:

- Displacement / Strain.
- Stress / Pressure.
- Cracking.
- Corrosion / Temperature.
- Live Loads.

A study of the most frequently used nondestructive methods to monitor the above-mentioned parameters was done. Nondestructive methods have proven to be fast, inexpensive and are applicable to all bridge types. They were found to be particularly advantageous for monitoring the corrosion of reinforced concrete bridges, when compared to destructive methods, because they enable a continuous monitoring of reinforcement condition and allow for measurements to be done at the level of the entire structure. However, determination of reinforcement steel corrosion with nondestructive methods is complex and may lead to wrong interpretation of results. To avoid misinterpretation it is recommended to combine several nondestructive testing methods, before making any conclusion about reinforcement steel corrosion.

PART A: ENERGY ABSORBING FENDER SYSTEMS

INTRODUCTION

Bridge pier protection is a concern of both the NJDOT and FHWA. Bridge Structures in navigable waterways are at risk of being damaged when struck by marine vessels. Currently, fender systems are installed around the piers as rigid barriers to provide protection. However, in many collisions, these barriers are themselves damaged or destroyed resulting in loss of life, bridge structures, ships and expensive repairs of the bridge protective systems. The objective of this study was to identify a Bridge Fender Systems that could absorb and deflect any impacts without damage to the system, the bridge structure, or the impacting vessel. This study, motivated by the increasing number of ship collisions with bridges (Table A1), required an extensive literature search into state-of-the-art protection systems used by other states. A study was also made of commercially available systems that are in use throughout the world.

Table A1: Major Ship Collisions with Bridges

Location	Yr	Lives Lost	Other Damages
CSX/Amtrak Railroad Bridge, USA	1993	47	Bridge/pier destroyed
Claiborn Avenue Bridge, USA	1993	1	
Hamburg Harbor Bridge, USA	1991	0	
Volga River Railroad Bridge, Russia	1983	176	Bridge/pier destroyed
Tjorn Bridge, Sweden	1980	8	
Sunshine Skyway Bridge, USA	1980	35	Bridge/pier destroyed
Pass Manchaca Bridge, USA	1976	1	
Tasman Bridge, Australia	1975	15	
Sidney Lanier Bridge, USA	1972	10	Bridge/pier destroyed
Old bridge in Portland Maine	1996		\$46 million to clean oil spillage
I-40 Bridge Arkansas river Oklahoma	2002	14	Bridge/pier destroyed
Casco Bay Bridge US Virginia	2002	0	No major Damage.

RESEARCH APPROACH

This study was approached in three stages:

- Identification of the existing technology which has been used for bridge fender protective systems by other states or countries.
- Identification of the State of the Art Systems that are the Energy Absorbing/Impact deflecting type that are either currently in use or commercially available.
- Rating of various designs based on cost-benefit criteria.

FINDINGS

A. The existing technology which has been used for bridge fender protective systems by other states or countries was grouped into six main categories:

- 1) Pile supported.
- 2) Retractable.
- 3) Rubber.
- 4) Gravity.
- 5) Hydraulic/pneumatic.
- 6) Floating systems.

The literature for laboratory testing of mechanical properties showed that composite fender Piles are viable substitutes for wood steel and pre-stressed concrete fender piles.

B. The literature search revealed energy absorbing fender systems that are commercially available and currently in use fall into three categories:

1. **Cellular Sheet Pile Dolphin and Fenders**

This is a pier protection system consisting of cellular sheet pile dolphin and fenders to demarcate the channel, designed to prevent or

minimize damage to the bridge piers due to vessel impact.

A similar system was able to absorb the impact and prevent damage to both bridge pier and the vessel in May 2002, at Casco Bay Bridge in Portland Maine.

2. **Donut Monopole Fender Systems**

A donut fender is a foam-filled fender, which can be designed to be slipped over a stationary monopole.

A similar system in the New York City port has been observed standing sentry for the pier it is protecting for nearly four years since its installation.

3. **Composite Pile, Fender, and Dolphin Systems**

Composite pile, fender and dolphin systems are designed to suit any situation. Fenders are secured to the outside of the composite pile to increase the energy absorption/deflection capabilities. Dolphins are used to deflect ship/barge as they negotiate narrow waterways or hairpin turns.

A similar system was constructed by hardcore composites for pier ends at Lewes, Delaware Ferry. On July 17, 1997.

- C. According to the AASHTO Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges, the expected impacting force depends on the type of vessels traveling in a water channel. It is suggested that final fender system design should take into consideration the risk of collision, which depends on the geometry of the channel and the size and number of vessels. Risk analysis is critical in the cost-effectiveness evaluation of alternative fender systems. This is

presented at length in the DESIGN PROCEDURES section of the Part A report.

- D. From life cycle cost analysis it was found that the costs of repairing bridge damage, and the costs of performing fender/bridge maintenance, if an inadequate protection system is used, are potentially much greater than the entire cost of installing an adequate protection system in the first place.

RECOMMENDATION

A protection system composed of **HARDCORE COMPOSITE PILE DOLPHINS, COMPOSITE TUBULAR PILES WITH STAY-IN-PLACE FORMWORK SURROUNDED BY COMPOSITE ULTRA HIGH MOLECULAR WEIGHT FACED FENDER PANELS** was recommended as the state-of-the art system for New Jersey Department of Transportation. This recommendation was achieved by rating six design alternatives based on their life cycle cost. Furthermore it was found that this system is similar to the one used at Casco Bay Bridge but with additions/modifications to facilitate the design of a 100% energy absorbing system.

The state –of –the-art system at Casco Bay Bridge in Portland Maine was reported to be able to absorb the impact and prevent damage to the bridge pier, bridge, and the vessel, in May 2002, when a 685-foot oil tanker transporting 11.3 million gallons of fuel struck the bridge fender system. It was further reported that about \$1 million only was needed to repair the fender system after the impact. This system, which cost about \$7million, was designed to absorb the energy of a 50,000-dwt vessel traveling at 5 knots and striking the fenders at a 15° angle (an equivalent of 46.25 MN lateral load). A schematic of the recommended system is shown in Figure A1. Details of the design concept are to be found in Volume II of the Final Report.

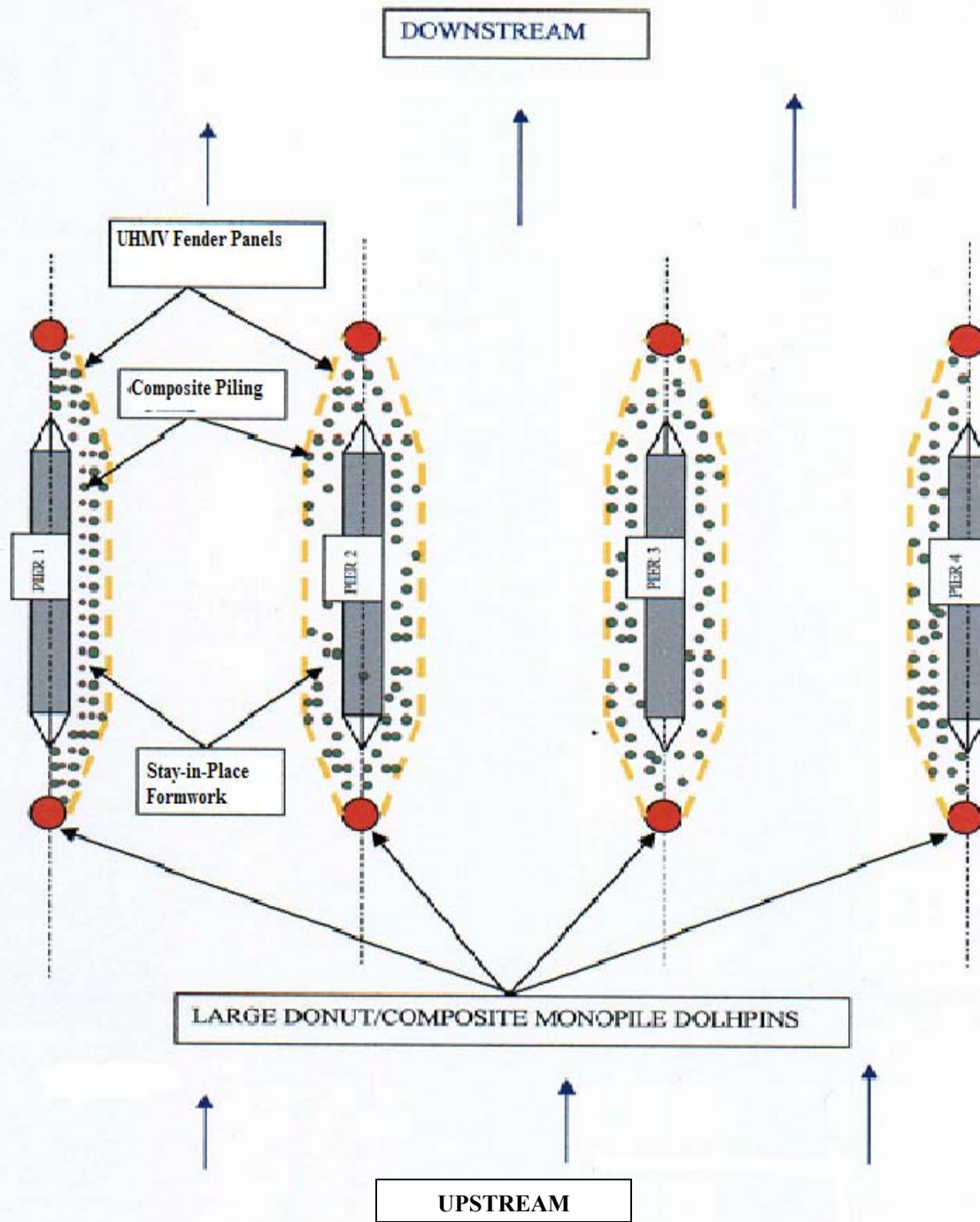


Figure A1 – Schematic of Recommended Energy Absorbing Pier Fender System (Plan)

PART B: PRE-CAST OR PREFABRICATED BRIDGE DECK SYSTEMS

INTRODUCTION

The Federal Highway Administration considers approximately 31.4 percent of the nation's bridges to be deficient. This concludes that a large amount of bridge rehabilitation and reconstruction projects will need to take place in order to keep roads and highways functioning at sufficient capacity. Many of these bridge projects will take place in urban areas where traffic and roadway congestion are a serious concerns. The sponsoring agencies and the communities served by them would benefit from technologies that would allow rapid completion of these projects. One such technology is precast concrete bridge superstructures, specifically precast bridge decks. This report is an exploration of the design and construction methods, as well as the performance of precast bridge decks that was accomplished through reviews of the current literature on the topic.

RESEARCH APPROACH

This study was approached in four stages:

- (1) Identification of all pre-cast or prefabricated bridge deck system types manufactured in NJ & other locations.
- (2) Search of Locations and History of Performance for the Identified Pre-cast or Prefabricated Bridge Deck Systems.
- (3) Cost comparison of the identified systems versus cast-in-place systems.
- (4) Life cycle cost analysis using for the identified systems.

FINDINGS

A. Precast/Prestressed bridge deck systems used in the United States and the United Kingdom were identified and grouped into two main categories as:

- 1) Total Precast Superstructures.
- 2) Precast Bridge Deck Panels.

B. The study revealed that, the first prestressed (and precast) bridges were built in the early 1950's. Despite having planned service lives of 50 years, the majority of these bridges were in good condition and were expected to last well beyond their planned service lives at the time of inspection in 1990. In fact, a smaller percentage of bridges built with precast/prestressed (pc/ps) concrete were found to be structurally deficient than those that were built with other materials, such as timber and steel in corresponding age and span categories. There was little difference in the percentage of structurally deficient bridges between bridges built with prestressed/precast concrete and those built with reinforce concrete

Segmental construction also employs the use of total precast concrete superstructure elements. An advantage of segmental bridges is that they can be built with minimal environmental impact to their surroundings. Segmental bridge construction is often used in environmentally sensitive areas or in areas of rough terrain where conventional bridge construction would be very difficult (Figure B1).



Figure B1. Segmental Bridge Construction

C. Unit costs for some segmental bridge pre-cast deck projects and cast in place bridge deck projects were discounted at 4% and their average present worth compared. The results concluded that the cost of segmental bridge with pre-cast deck is about 40% less than the cost of segmental bridges with cast in place decks

DISCUSSION ON THE FINDINGS

Condition studies of precast bridge decks indicate that they have performed equally as well, if not better than their cast-in-place counterparts. In many cases, bridges built with precast components have well surpassed their designed service lives. However, the technology is not flawless. There have been problems, particularly in regard to segmental and partial depth precast panel construction. Segmental bridge construction requires quality workmanship and thorough inspection and testing in order to insure proper bonding of the post-tensioning strands and composite action of the precast segmental units. Testing has shown that the problems associated with partial depth precast panels in the past can be mitigated by designs that provide for transverse and longitudinal continuity through adjacent panels.

On several bridge deck projects, substantial cost savings have been documented and

attributed to the use of precast bridge deck components over cast-in-place decks due to the reduction of formwork and manual labor. The reduced construction time and potential for longer service lives associated with precast bridge decks add to their cost efficiency.

There are several design and construction innovations pertaining to precast bridge decks that are being studied but have not been widely implemented as of yet. Some examples are High Performance Concrete (HPC), Ultra-High Performance Concrete (UHPC) and Fiber Reinforced Polymer (FRP) composite panels. Through increased strength and resistance to corrosion, these innovations have the potential to increase performance and greatly extend the service lives of bridge decks beyond what is achievable through conventional construction methods.

RECOMMENDATION

This research suggested that precast bridge decks have several advantages over those that are cast-in-place including faster construction schedules, longer services lives and potentially greater cost efficiency. The use of precast bridge decks in conjunction with new construction materials such as High Performance Concrete and Fiber Reinforced composites is recommended.

PART C: SMART BRIDGES

INTRODUCTION

The deterioration of the U.S. infrastructure has reached alarming levels due to the large number of structures that are classified as functionally obsolete or structurally deficient. The large costs required for rehabilitation and replacement have led to the development and the application of methods to prioritize the rehabilitation/replacement process while ensuring the safety of the public. These methods, that use asset management principles, depend on accurate assessments of the conditions of the structures under consideration and true estimates of their useful lives. To obtain a good understanding of the behavior of structures under actual conditions, monitoring the behavior of large structures such as bridges, tunnels, and dams has become increasingly critical.

A “smart bridge” can be defined as a bridge that has the ability to monitor its structural behavior and other performance during construction as well as under service loads and maximum loading conditions. Smart bridges usually utilize different instruments to monitor various physical parameters under different weather and loading conditions. Listed below are five of the most important parameters of concern to engineers:

- Displacement / Strain.
- Stress / Pressure.
- Cracking.
- Corrosion / Temperature.
- Live Loads

Monitoring bridge displacements is a main concern because excessive displacements create public anxiety even though they may not be indicative of hazardous conditions. Stresses are the main criteria for structural safety and when they exceed permissible levels damage as well as local failure or

structural collapse may ensue. The presence of cracks should also be carefully monitored particularly when they have the tendency to grow. Corrosion leads to large reduction in a member’s load carrying capacity due to the loss in section and the cracking and spalling that they may induce. Large temperature variations also lead to changes in structural behavior. They affect material properties and may lead to high levels of stresses and the development of cracks.

RESEARCH APPROACH

This study was approached in four stages:

- (1) A list was compiled of all Smart Bridge installations that have been constructed throughout the United States and Canada, along with their types and locations.
- (2) The strengths and weaknesses of each installed system were analyzed and a list detailing the particulars prepared.
- (3) Recommendations for improvements of the systems were provided.

FINDINGS

A literature search provided the following findings:

- A.** Degradation caused by cracking, corrosion, etc., can compromise a bridge’s ability to fulfill its intended function. High transient loads and severe environmental conditions are the major causes of degradation. The effects of high transient loads can be addressed through adequate member proportioning and design details. These loads can be monitored by various means including Weigh-In-Motion systems for live loads.

B. Environmental effects on concrete bridge members include carbonation, sulfate attack, alkali-silica reaction, freeze-thaw cycles, and ingress of chlorides and other harmful chemicals. Chemicals invade the pore system of concrete and initiate chemical and/or physical reactions, typically resulting in the formation of expansive by-products. The forces of the by-products often produce cracking of concrete. The most damaging consequence of these reactions is the depassivation of steel, with corrosion as a result. Corrosion of steel produces cracking, typically along the length of the steel, and eventually leads to spalling of concrete. The end of the service life of the bridge occurs when the accumulated damage in the bridge materials exceeds the tolerance limit. The service life of the bridge can, however, be extended by performing periodic repairs. The need and extent of repairs to a structure are established by performing periodic condition assessment reviews of the structure.

Currently, NCHRP Report 312 provides a comprehensive summary for estimating the state of a concrete bridge superstructure element. In addition, several state DOTs have established their own practices for condition assessment of bridge decks. Qualitative measures of corrosion are obtained during the mandatory biennial bridge inspection. Inspection reports give ratings of bridge members based on the level of deterioration. Different rating scales have been developed by different agencies and groups such as FHWA, state DOTs and research agencies working with bridge management systems such as PONTIS. As per the FHWA guidelines, each member is given a rating between 0 and 9, where 9 indicates a perfect member. Bridges with ratings lower than 4 are classified as needing rehabilitation.

C. Smart bridges are instrumented for health monitoring purposes to provide information on their behavior and help assess their safety. A bridge is safe as long its members are capable of withstanding the applied loads. Although much effort has been expended to develop methods to predict and monitor the load carrying capacity and the deterioration of bridge members, little effort has been directed to estimating the magnitude and intensities of the applied loads. For short to medium span bridges, the most critical loads are those caused by the crossing of the heavy trucks. Hence, the application of WIM technology is an essential part of any smart bridge system.

The most commonly used WIM systems were reviewed. These systems include pavement-based systems such as: bending Plates, Capacitive Mats, Load Cells, as well as Piezoelectric and Quartz Cable systems (Table C1).

Table C1. Summary of WIM System Accuracy

TECHNOLOGY	Accuracy
Bending Plate	0 to 12%
Capacitive Mat	0.5 to 1.5%
Load Cell	0 to 6%
Piezoelectric	3 to 30%
Quartz cables	<10%
B-WIM	0 to 3%

One drawback of pavement-based systems is that they require continuous maintenance of the pavement in order to reduce the dynamic effects and guarantee good measurement accuracy. In addition, piezoelectric and Quartz cable WIM systems must be placed in arrays to further reduce the dynamic effects. The heavy maintenance schedule and redundant

placement of cables increases the life-cycle costs of pavement-systems (Table C2). To overcome these disadvantages, several highway and transportation agencies are showing renewed interest in Bridge Weigh-In-Motion (B-WIM) systems.

B-WIM is the process by which axle and gross vehicle weights are automatically collected for trucks traveling at highway speeds over an instrumented bridge. B-WIM systems involve attaching strain transducers to bridge structural members and placing axle detectors on the bridge road surface. The axle detectors provide information on truck velocity, axle spacing, and the position of the truck. This information, along with the measured strains, is used by the bridge weigh-in-motion algorithm to determine axle and gross vehicle weights. Because the measurements are taken over the relatively long period during which the vehicle is passing over the structure, dynamic effects have less influence over the results than pavement systems that normally “sense” each truck axle weight over very short durations. This is especially true when B-WIM is used on bridges with relatively good riding surface conditions, or when used in culverts (as is the practice in Australia) where the soil provides additional damping.

The application of data collected by smart bridges for the load-capacity evaluation of highway bridges and assessing their safety using the newly developed AASHTO Load and Resistance Factor Rating (LRFR) procedures is discussed in the final report. The rating factor, or alternatively, the reliability index, for particular bridge members can be obtained based on the WIM truck weight data combined with the data obtained from steel reinforcement corrosion and the response (strain and/or displacement) of bridge members to known and random loads. Because they provide objective measures of structural safety, the rating factors and reliability indexes constitute the most important parameters that bridge engineers should use when

making decisions and setting priorities concerning bridge closings, postings, maintenance or rehabilitation.

Table C2. Estimated Average Annual Cost for Maintaining a Pavement -Based WIM System Installation (Iowa Study)

Cost Items	Unit Cost/ installation
Pavement rehabilitation	\$2,280
Other site maintenance	\$2,500
Sensor replacement	\$825
Electronics replacement	\$750
Calibration costs	\$11,000
Office costs	\$1,150
Travel and per diem	\$2,500
Total Annual Cost	\$21,000

RECOMMENDATION

Currently bridge ratings are set, based on a subjective assessment by a team of inspectors. Hence, there is a need to develop more objective and comprehensive test and evaluation procedures based on continuous monitoring of the following:

- Corrosion – presence and rate.
- Cracking – location and opening.
- Loads – number and magnitude.

The three items listed above point to the three primary causes of deterioration in the structure. In addition, the monitoring program can be extended to detect changes in the stiffness and reactions. The damage assessed through these continuous monitoring programs can then be integrated into the existing guidelines to produce a more informed judgment about the condition of the structure.

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