Life-Cycle-Cost (LCC) Model for the Design of a Bridge Vibration Monitoring System (BVMS)

Ahsan Zulfiqar, Miryam Cabieses, Namra Khan, Andrew Mikhail

George Mason University(GMU)

Corresponding author's Email: azulfiqa@masonlive.gmu.edu,

Abstract: The average age of the 607,380 bridges in the U.S. is 42 years old. All bridges are required to be inspected every two years, and the frequency of these inspections increases as they age. The current bi-annual cost to inspect all bridges is $2.7 billion and each bridge requires 1-3 days for on-site inspection, depending on the complexity of the bridge. As the age of bridges increases, the frequency and duration of the inspections increases. Advances in technology provide an opportunity to reduce the costs and time, and improve the quality of bridge inspections by migrating from a periodic bridge inspection paradigm (e.g. once every 2 years or less) to an event-based inspection (e.g. inspect only when needed).

1. Introduction

Bridges are a part of modern the transportation system of a modern economy, used to connect highways, cross rivers, and join countries. Bridges in the U.S. are owned by the Federal Highway Administration (FHWA) states or local municipalities. Federal mandate bridges in sound condition must be inspected every two years. Bridges in inferior conditions must be inspected more frequently.

The bridge inspection process is a manual inspection process (Ryan et al., 2006). The on-site inspection takes 1-3 days for the inspection (Ryan et al., 2006). Preparation of bridge inspection takes several weeks of planning, Currently, the manual inspection, on averages, costs $4500 per inspection, which makes a total bi-annual inspection cost of $2.7 billion (How, C. 2014)

With over 607,380 bridges in the country with average age 42 years fatigue damage is becoming a serious concern for the bridge owners as manual inspections continue to reveal structural deficiencies that are costly to fix (How, C. 2014) The bridge structural deficiencies from ageing result in increased frequency of the inspection cycle from 2 years to 6 months. This quadruples the bi-annual inspection cost. This also increases delays to users of the bridge closed during inspections.

1.1. Bridges and Bridge Failures

The four main types of bridges are arch, beam, cantilever, and suspension; the scope for this project will be limited to the Theodore Roosevelt Bridge, which is a beam bridge in Washington DC. There are three main sections to a beam bridge: the deck, the substructure, and the superstructure. Each section contains subsections, and the inspection thoroughly details every step for inspecting each part of every subsection. The FHWA defines a set of general inspection procedures as part of its strict inspection protocol, and each major task has several minor steps under it. Unfortunately, this well-intentioned plan has several flaws, and the most glaring of these flaws is the lack of quantitative data in the inspection procedure. This has many impacts, because the once-rigid standards of inspection are now being warped to the opinions of the inspectors, who may not always be right.

As a bridge gets older, its behavior changes and these changes happen due to the change in the actual components of the bridge. A change in the material of the component can cause a change of the behavior of the bridge. These changes are caused by external factors that impact the bridge material such as mass loss, which can come from rusting of metal or deterioration of concrete and many other factors cause a change in the mass of the material.

1.2. Repairs

Historical data were collected from bridges that aged between 40-50 years (How, C. 2014). These historical data are the number of repairs needed for a bridge throughout its lifetime. An observation was made from the data collected about the

Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
April 30, 2015
A Regional Conference of the Society for Industrial and Systems Engineering

number of repairs needed as bridges age. The number of repairs needed were increasing as the bridges get older, which is an expected result due to the deterioration of the bridges' material and other external factors that affect the behavior of the bridge. Figure 1 shows the number of repairs needed for 17 different bridges throughout their lifetime.
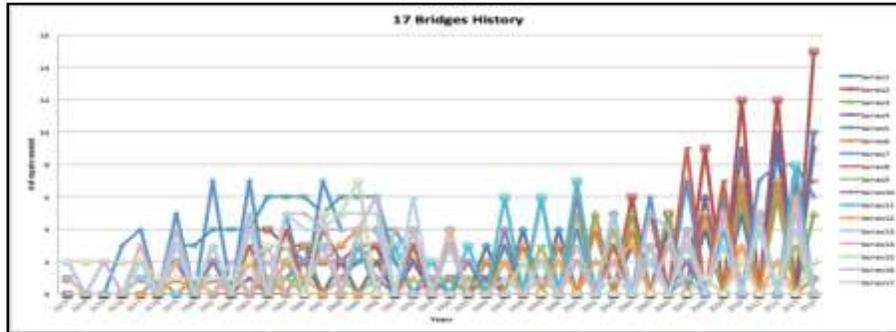

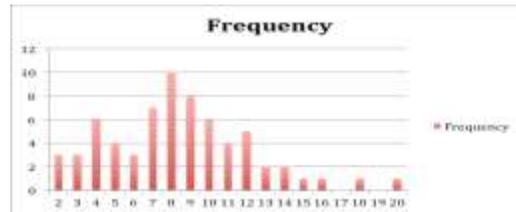Figure 1. Bridge Repair History for 17 different Bridges

Figure 2. Frequency of Repair Events (time it takes for an identified deficiency to be repaired)

From Figure 2, it can be seen that it takes almost 8 years for a repair to be made from the time it is identified. This delay, in response, has an impact on the bridge's behavior. The main effect can be seen in the second half of the bridge's lifetime where the number of repairs needed increases exponentially. The scientific explanation of this phenomenon is the repairs identified in the beginning cause complications as the repair time increases. When a defect is identified in a specific part of a bridge it infers that this part of the bridge is not handling the stress that it is designed to handle which causes another part of the bridge to handle that stress. The other part is now handling more stress than it is designed so it fails, which causes a chain in increasing stresses. By the time the repair is made for the first part, other parts have already been defected due to the extra stress that was put on them.

2. Stakeholder Analysis

There are five primary stakeholders of the bridge inspection system: (1) Federal Highway Association (FHWA), (2) Department of transportation (DOT), (3) Design Engineers, (4) Inspection Team and the (5) Construction team. Bridge Users are are the secondary stakeholders. There is a tension between the bridge inspectors and their management. Bridge inspectors are obligated to other stakeholders to perform the highest quality inspections. The DOT and state DOTs need to complete the inspections with high quality but low cost and time. If the inspection quality could be improved and the time of cost and inspection reduced, the inherent tension would be eliminated.

3. Problem/Need Statement

A system is needed to reduce the time and cost of bridge inspections for aging bridges. The system must also improve the quality of the inspections.

4. Concept of Operations

The proposed concept of operations is to transition from a previously Periodic Inspection process that would inspect bridges every 2 years to an Event-Based process that will only inspect bridges when there is a deficiency detected. The previous inspection process for each bridge would take, on average, 3 days, where the alternative system will only take, on average, 1 day, since only a part of the bridge is inspected. This is due to the fact that the proposed alternative will identify the optimal location where a deficiency is found.

Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
April 30, 2015
A Regional Conference of the Society for Industrial and Systems Engineering

5. Bridge Vibration Monitoring System

The support the Event-based concept-of-operations, a Bridge Vibration Monitoring System (BVMS) is required. All bridges undergo some form of dynamic loading, which causes them to vibrate. Each bridge has a unique vibration fingerprint which comes from the mass, stiffness, and material of the specific bridge. Changes in the vibration fingerprint caused by the deficiencies can be detected using accelerometers. The initial fingerprint frequency of the bridge will be recorded from each accelerometer. The system will continuously monitor the readings from the accelerometers. These accelerometer frequencies for each component will be sent through either cables or a wireless network to the DAU. After the information is sent to the DAU, if it notices a change in the frequency when compared with the bridge fingerprint, it will send an alarm to the base if the problem is consistent. Upon receiving an alarm from the DAU, an inspector from the base will perform a manual inspection of the bridge at the location detected by the accelerometer.

For example, there are 31 fracture-critical locations found on the Theodore Roosevelt Bridge with the highest shear and moment, therefore, there will be 31 natural frequencies obtained by the placed accelerometers. Each natural frequency will be identified by changing the electric signals obtained from the accelerometers in time domain to frequency domain. This is calculated by identifying the highest peak of the Gaussian distribution from the frequency domain. An analysis of the input reference of 31 natural frequencies per day for a year were used to identify customary distribution has natural frequencies with a standard mean of 5, and standard deviation of 0.15.

Each natural frequency of the 31 accelerometers is sent to the DAU per day, however, in order to know if the condition has changed over time, the natural frequencies will be monitored for a threshold of 7 consecutive days. The 7 day threshold is to verify that the natural frequencies change was due to a deficiency found instead of external factors affecting its change. If the natural frequency is one standard deviation away it will be considered in a good condition, if its two standard deviations away it's considered in fair condition, and so forth. These natural frequencies will be generated with a random Gaussian distribution number generator, generating numbers between 4-7 Hz most frequently, although the given range is from 0-10 Hz.

Since, these natural frequencies will be obtained per day, there is an Omega Array that resets the previous randomized values to verify that it is not stored allowing the new generated number to take the spot per day. Another Array called Broken Array exists in order to store the identified condition of each natural frequency per day sending the obtained data to the DAU. If the natural frequency were considered as good condition, it will add in the for-loop 0, however if it were considered in fair or poor condition, the for-loop would add 1. Therefore, after seven consecutive days it will send the data to the base from the DAU if this for-loop has more than 3 fair or poor conditions identified for the 7- day threshold.

Although the simulated program is based on the real world, peak hours are not necessary, as it will only change the value of the natural frequency generated but not the probability of the value to be generated. The outcome allows the user to see the day; the accelerometer number that shows the location it was placed in, the value randomized and its condition per component.
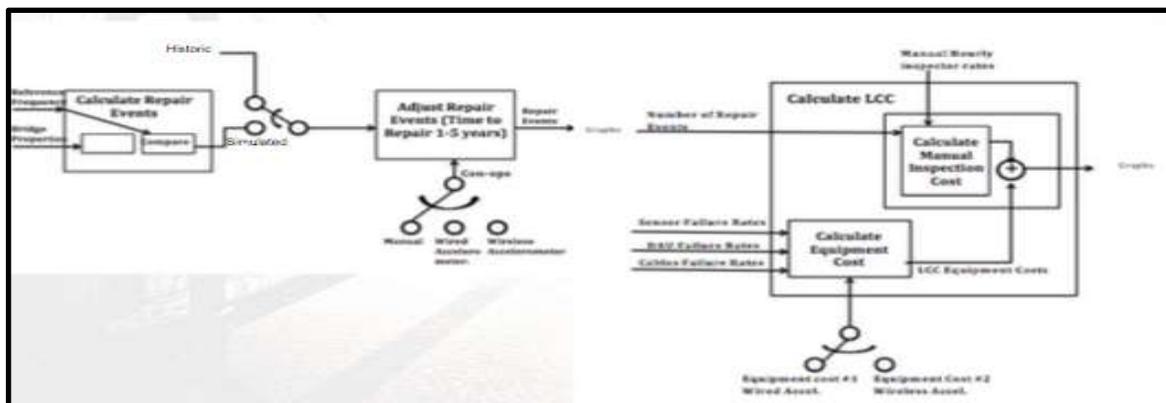
6. Life-cycle Cost Model

Figure 3. Method of Analysis consists of three main functions: Calculate Repair Events, Adjust Repair Events, and Calculate LCC

Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
April 30, 2015
A Regional Conference of the Society for Industrial and Systems Engineering

The main component in the method of analysis is: *Calculate Life Cost Cycle*. The *Calculate Repair Events* is the Vibration Analysis, which uses the event inspection's reference natural frequencies acquired through discussions with industry experts, in comparison with the randomly generated Gaussian numbers simulated in order to replicate what the Theodore Roosevelt Bridge would encounter, and derive how many repair events are required (Lattanzi, D. 2014). The set of inputs are the unique fingerprints of each bridge, such as their structure, damping, stiffness, mass, and length.

The second block is the Adjust Repair Events, inputting either the generated repair events or the historical data obtained from 17 VDOT bridges. This serves as a validation to see if the frequency of generated repairs matches the historically identified repair events. With this analysis, the exponential increase of repairs needed due to the manual inspection using the historical data vs. the new constant linear distribution profile of repairs needed obtained due to the use of sensors derived from the Vibration Analysis.

Knowing how main repairs are needed depending on the profile per design alternative lead us to the Calculate Life Cycle Cost, which has two subdivisions of calculate manual inspection cost, and calculate equipment cost. Identifying number of repair events direct us to calculate manual inspection cost per alternative. Each alternative then has its own equipment cost. Such inputs are the sensors, DAU, communication, and power failure rates.

7. Concept-Of-Operations Life Cycle Costs Analysis

The life cost of the system is divided into two parts: (1) Periodic with Manual Inspection cost for the current system versus (2) the cost of the Event-based with BVMS (Wired Accelerometers Alternative) and (3) the cost of the Event-based with BVMS (Wireless Accelerometers Alternative). Since the life expectancy of a bridge is 50 years, the cost of the alternatives is being calculated for a 50-year lifespan.

7.1. Periodic with Manual Inspection (current)

The current manual inspection cost is calculated by the following equation:

Manual inspection cost = (cost per inspection) * (number of inspections)   (1)

The cost per inspection for the Theodore Roosevelt Bridge is $30,000 (DOT, n.d). The number of inspections needed for this bridge is calculated to be 30 inspections during the 50-year lifespan. These 30 inspections come from a biannual inspection cycle for the first 40 years of the bridge and an annual inspection for the last 10 years.

7.2. Event-based with BVMS (Wired/Wireless Accelerometers Alternative)

The cost is based on two factors: the equipment cost and the inspections needed.

7.3. Equipment Cost

The equipment replacement is an important factor since they are subject to failure due to their life span. This is analyzed in a Best, Expected, and Worst case scenario based upon the life span of the equipment used.

7.3.1. Event-based with BVMS (Wired Accelerometers Alternative)

Total Wireless Cost = (Accelerometer quantity*quantity cost) + (installation) + (cables (power & communication *length)) + (DAU) + (software) + (Communication system) + (QA Inspection)   (2)

7.3.2. Event-based with BVMS (Wireless Accelerometers Alternative)

Total Wireless Set cost = (Accelerometer quantity*quantity cost) + (installation + (microcontrollers & power)+(DAU) + (software communication system) + (QA Inspection)   (3)

7.4. Inspection cost

The manual inspection cost is associated since the inspectors will only be inspecting the area of deficiency instead of the whole bridge. The inspection cost for both Event-Based Alternatives is calculated using the following equation:

Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
April 30, 2015
A Regional Conference of the Society for Industrial and Systems Engineering

Total inspection cost = (Number of inspectors*rate*hours) + (Equipment rental) + (Analysis)   (4)

The number of inspections needed was calculated based on historical data that was shown in previous sections. A total cost for inspections was calculated for the 50 years life span based on the following equation:

50 year inspection cost = (Total inspection cost) * (Number of inspections needed)   (5)

7.5. Total Cost

The total cost for the two Event-Based alternatives were calculated based on the following common equation:

Total Life-Cycle Cost = (50 years Inspections Cost) + (50 years Equipment Cost)   (6)

The 50-year Equipment Cost was calculated according to the following equation:

50 years Equipment cost = (Number of set replacement) * (price per set)   (7)

The following graphs explain the prices for Event-Based alternatives (Wired Accelerometers Alternative and the Wireless Accelerometer Alternative) with best, expected and worst costs compared to the cost for the current manual process.
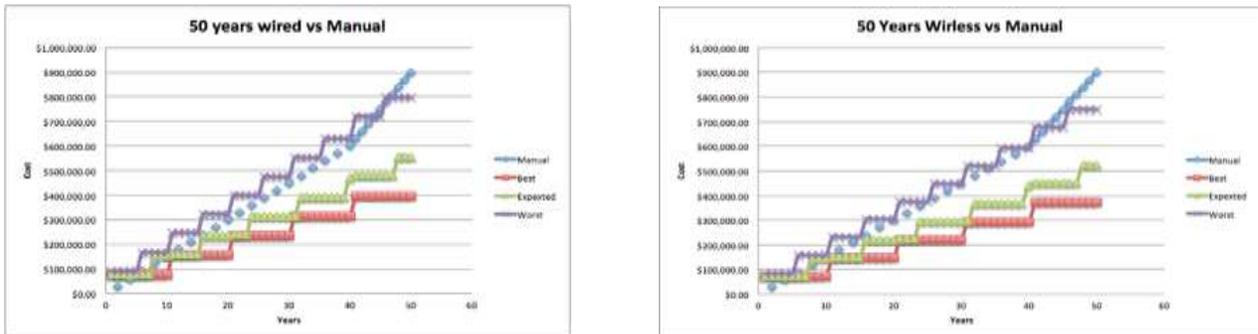

Figure 4. Cost comparison between the Event-Based Alternatives and the Manual Inspection

8. Business Case

Based on the data obtained from costs calculated life cycle costs, it can be concluded that the Event-Based BVMS has reduced the cost and caused savings of 45% of the current manual inspection in the wired accelerometers alternative and 48% in the wireless accelerometer alternative.

Table 1. Total cost savings of the proposed alternatives

Total Cost Savings			
System Lasts	5 years	8 years	10 years
50 years monitoring	Worst	Expected	Best
Event Based Inspection			
Wired	$900,000-$789,412.00 = $110,588 %12	$900,000-$495,316.00 = $404,684 %45	$900,000-$392,128.00= $507,872 %56
Wireless	$900,000-$743,330.00 = $156,670 %17	$900,000-$466,514.75 = $433,485.25 %48	$900,000-$369,087.00= $530,913 %59
Periodic Inspection			
Manual	$900,000.00	$900,000.00	$900,000.00

Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
April 30, 2015
A Regional Conference of the Society for Industrial and Systems Engineering

From Table 1, it can be seen that the Wired alternative suggests cost savings of 12% to 56% and the Wireless alternative suggests savings of 17% to 59% when compared to the current manual inspection cost. Furthermore, the manual inspection has one constant cost that does not change depending on the type of cost, the time period or how long the system lasts.

Additionally, analyzing just the manual inspection cost for the expected case, Event-Based reduces the cost by 98% for both the wired and wireless alternative. Since the manual inspection after the alarm is exactly the same for both wired and wireless alternative, the cost saving the manual inspection is also the same for both solutions.

8. Recommendations

According to the total cost savings shown in Table 1, the Event-Based alternative with the mounting of wireless sensors will have the highest cost savings of the three alternatives. The mounting of wireless sensors has an expected life cycle of 8 years, with a 48% cost savings compared to the wired sensors that yields cost savings of 45%. The wireless mounting of sensors is recommended since it eliminates the installation of costly wires. The difference in the cost of the wired sensors and wireless sensor is because cables are installed for the wired sensors and microcontrollers are used for the wireless sensors. As shown in the equipment cost section, installing cables is more expensive than mounting microcontrollers. Therefore, the wireless mounting of sensors is recommended since it provides the highest cost savings.

9. References

Ryan, T. (2006). *Bridge Inspector's Reference Manual* (Rev. Dec. 2006. ed.). Washington, D.C.: Federal Highway Administration.

Serridge, M., & Licht, T. (1986). *Piezoelectric Accelerometer and Vibration Preamplifier Handbook*. Nærum: Brüel & Kjær.

Schnellinger, J., & Kulwanoski, G. (2004, February 1). The Principles of Piezoelectric Accelerometers. *Sensors Online*.

Accelerometer Mounting and Installation Techniques. (n.d.). Retrieved March 10, 2015, from http://www.wilcoxon.com/knowdesk/mounting.pdf

Weber, M. (n.d.). Accelerometer Mounting. Retrieved March 10, 2015, from http://www.mmf.de/accelerometer_mounting.htm

2013 Report Card for America's Infrastructure. (n.d.). Retrieved March 10, 2015, from http://www.infrastructurereportcard.org/

Cook, W. (2014). Bridge Failure Rates, Consequences, and Predictive Trends. Retrieved March 10, 2015, from http://digitalcommons.usu.edu/etd/2163/

Deficient Bridges by State and Highway System. (n.d.). Retrieved March 10, 2015, from http://www.fhwa.dot.gov/bridge/deficient.cfm

Bridge Construction. (n.d.). Retrieved March 10, 2015, from http://www.ce.udel.edu/courses/CIEG 486/Bridge.pdf

What We Do. (n.d.). Retrieved March 10, 2015, from http://www.fhwa.dot.gov/

Department of Transportation. (n.d.). Retrieved March 10, 2015, from http://www.dot.gov/

Rouse, M. (n.d.). What is WIPS (wireless intrusion prevention system)? Retrieved March 10, 2015, from http://whatis.techtarget.com/definition/WIPS-wireless-intrusion-prevention-system

How, C. (2014, October 20). Information Regarding the Current Inspection Process [Personal interview].

Lattanzi, D. (2014, September 1). Information Regarding the Current Inspection Process [Personal interview].