

# **Design of a Bridge Inspection System (BIS) to Reduce Time and Cost**

**Ahsan Zulfiqar**

**Miryam Cabieses**

**Andrew Mikhail**

**Namra Khan**

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**Department of Systems Engineering and Operations Research George**

**Mason University**

**Fairfax, VA 22030-4444**

**October 08, 2014**

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# 1.0 Context

## 1.1 Current Bridge Inspection System

The Federal Highway Administration (FHWA) is an agency within the U.S Department of Transportation whose mission is to provide stewardship over the design, construction, maintenance and preservation of the Nation's highways, bridges and tunnels. This department is under the administration of 607,380 bridges, which include the regions of D.C and Puerto Rico as states. The average age of these bridges is 42 years, however, most exceed the lifetime they were built to have. Hundreds of thousands of civilians use bridges as a means for transportation. In order to guarantee civilians with safety, FHWA conducts bridge inspections every two years. The current bridge inspection process is manual, involving visual and aural inspections that are both time consuming and costly [15].

The FHWA requires evaluation of all bridges however; it is costly having a bi-annual inspection cost of \$2.7 billion for the U.S. where the average inspection cost per bridge ranges from \$4,500-\$10,000. This requires closing lanes for the span of the inspection, which can take 1 to 3 days causing traffic congestions. With the rapid growth of highway transportation and the dispersed age distributions of bridges, fatigue damage is quickly becoming a serious concern. Therefore, the demand to inspect bridges before the 2-year period is rapidly increasing as the condition of these bridges deteriorates. To assure safety and prevent any hazardous damage of collapsing bridges as has previously occurred the inspection period for these structurally deficient bridges ranges from 6 months to a year [9].

## 1.2 Structurally Deficient Bridges

Over time, the effects of nature and man cause bridges infrastructure to deteriorate more and more, if unaddressed, the smallest of cracks can result in devastating collapses. A major concern are structurally deficient bridges which are bridges rated in poor condition classified as such due to the fact that its load carrying capacity is significantly below current design standards. According to the American Society of Civil Engineers as of 2013 over 12% of the bridges in twenty-one states in the United States have structurally deficient bridges shown on Figure 1 [6].

These bridges are a prominent cause for concern due to the lack of safety they provide to the public. Inspecting these structurally deficient bridges prior than the 2-year period is essential in order to detect, and prevent bridge failures increasing the maintenance cost associated with the inspection process [9].

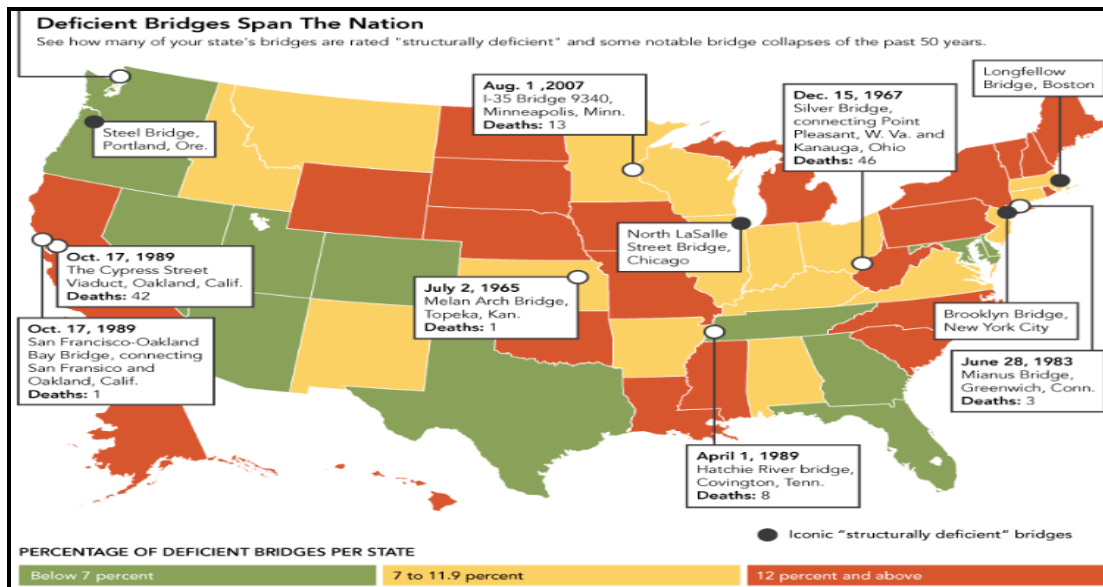


Figure 1: Deficient Bridges in the U.S.

## 1.3 Types of Bridges

The FHWA administers 607,380 bridges that vary in the type of material it is consisted of, the usage of the bridges as well as its structure. Under the classification of structure there are approximately more than 16 types defining the parts that need to be inspected, the time required, and the necessary equipment for inspection. Bridges classified by material define the age and how it needs to be replaced or repaired. The final classification of bridges is defined by use, which demonstrate the frequency that the capacity of the bridge is utilized.

The four main structure of bridges are the Arch, Beam, Suspension, and Cantilever. One of the oldest types of bridge in existence is the Arch bridge. They date back to the pre-Roman era and have been extensively in use because of their natural strength. An Arch bridge can be visualized as two parts of a whole, the curved bottom across the landscape and a flat span. The weight on an arch bridge is transferred outward along the curve of the arch to the supports at each end. As a consequence, the supports, called abutments keep the ends of the bridge from spreading out.

A beam bridge is the most basic type of bridge that can be constructed. It consists of a horizontal beam that is supported on the ends. Any weight that is on the bridge is transferred from the horizontal beam to the vertically supported ends. A beam bridge is also called a girder bridge, and the supported ends are often known as piers. The beam itself is built from materials that are strong, yet flexible, so that it is able to support its own weight as well as the weight on the bridge. When a weight pushes down on the horizontal beam, the beam stretches at the bottom and compresses on the top. This is commonly called tension and compression.

Suspension bridges are majestic due to the span distances they cover. They usually appear light and strong, and can run longer than any other kind of bridge. As the name suggests, a suspension bridge suspends the causeway from huge main cables, which extend from one end of the bridge to the other. These cables rest on high towers and are

secured at each end by anchorages. The towers help the main cables to be extended over long distances, and hence derives the majestic look. In the case of these bridges, the cables to the anchorages carry the weight of the bridge. The anchorages in turn are embedded in either solid rock or heavy concrete blocks. Inside these anchorages, cables evenly distribute the load and prevent them from breaking free.

A cantilever bridge is the last major type of bridge where two horizontal structures support a third horizontal structure on which a load is carried. The two horizontal structures must be anchored, and this must be done well. Cantilever bridges are a modified form of beam bridge, where the support instead of being placed at the end, is placed somewhere in the middle of the span. A cantilever is a structure that is unsupported at one end but supported at the other, very similar to diving boards in a swimming pool. This configuration made longer spans possible and wider clearance beneath.

## **1.4 Bridge Components**

There are four main bridge components which vary depending on the kind of bridge structure. These components are the deck, superstructure, substructure and truss.

The deck is the roadway portion or surface of a bridge. It is where the most external load is applied due to the traffic on the bridge consisting of expansion joints, sidewalks and railings, and shoulders. This bridge component is composed of concrete which is critical to know when performing the inspection. In concrete, inspectors look for things such as cracks and its cause which involve structure, flexure, shear, crack size, nonstructural, and crack orientation.

The superstructure are the components that take the load from the deck exerted by external forces and transfer them to the substructure. It consists of the floor beams, girders, bearing and stiffeners. The superstructure is generally composed of metal and it is where the most common failures are found. A failure in one of the superstructure may result in the collapsing of the bridge, therefore inspectors tend to pay close attention to these components.

The substructure are the components that receive the loads from the superstructure and transfers them to the ground. The substructure is generally made of concrete, consisting of abutments or end-bents, columns, wall piers or interior bents, footings and piling.

Trusses are organized as straight elements that are connected at the ends by hinges to develop a secure arrangement. The truss consists of a grouping of triangles that are manufactured from straight and steel bars. On application of loads on the truss joints, forces are communicated to the truss elements. The steel truss bridge members are in compression or tension making this component possess a high ratio of strength to weight.

### 1.4.1 Main Components and Failure Types

As shown in Figure 5, the main components that a bridge may be composed of are listed, which consists of the deck, substructure, superstructure, and truss. Associated with these components is the kind of material the component is made of as well as the most common failure types that correspond to these components. The failure types that are bolded, however, consist of the prominent failure types known to cause bridge failures. The list consists of section loss, structure critical point, fatigue, and corrosion [7].

Component	Material	Failure Types
<b>Deck</b>	Concrete	<b>Section loss</b>
• Roadway		Primary member damage (ex: collision...)
• Side walk		Columns with spalling and rebar section loss
<b>Substructure</b>	Concrete	<b>Structure critical point (ex: Fracture critical...)</b>
• Abutments		Severe deterioration
• Piers		High stress area
<b>Super-Structure</b>	Metal	Cracking
• Floor beams		<b>Fatigue (less stiff)</b>
• Girders		<b>Corrosion (Loss of mass)</b>
• Stringers		Missing connection
<b>Truss</b>	Metal	Bending (due to high stress)

Figure 5: Main Components & Failure Types



As previously stated, the most prominent failure types are section loss, structure critical point, fatigue, and corrosion since it contains the highest percentage to cause a bridge failure. Currently the general bridge inspection process requires these components to be physically and visually examined and evaluated. Visually examined meaning examination of these components by simple eyesight and prior experience, and physically examining where the use of equipment is required to obtain objective results. Therefore, the current inspection method consists of either visual and/or physical inspection. The chart below identifies the associated current inspection method for these main failure types.

<b>Material</b>	<b>Failure Types</b>	<b>Inspection Method</b>	<b>Percentage to cause failure</b>
<b>Metal</b>	Cracking	Visual/Physical	
	<b>Fatigue (less stiff)</b>	<b>Physical</b>	<b>13.05%</b>
	<b>Corrosion (Loss of mass)</b>	<b>Visual/Physical</b>	<b>3.26%</b>
	Bending (over load)	Visual	
	Missing connection	Visual/Physical	
<b>Concrete</b>	<b>Section loss</b>	<b>Visual/Physical</b>	<b>20.65%</b>
	High stress area	Visual/Physical	2.17%
	<b>Structure crack at critical point (ex: Fracture critical...)</b>	<b>Visual/Physical</b>	<b>16.3%</b>
	Severe deterioration	Visual	2.17%

Figure 6: Percentage of each failure cause [7]

## 1.5 Bridge Inspection Process

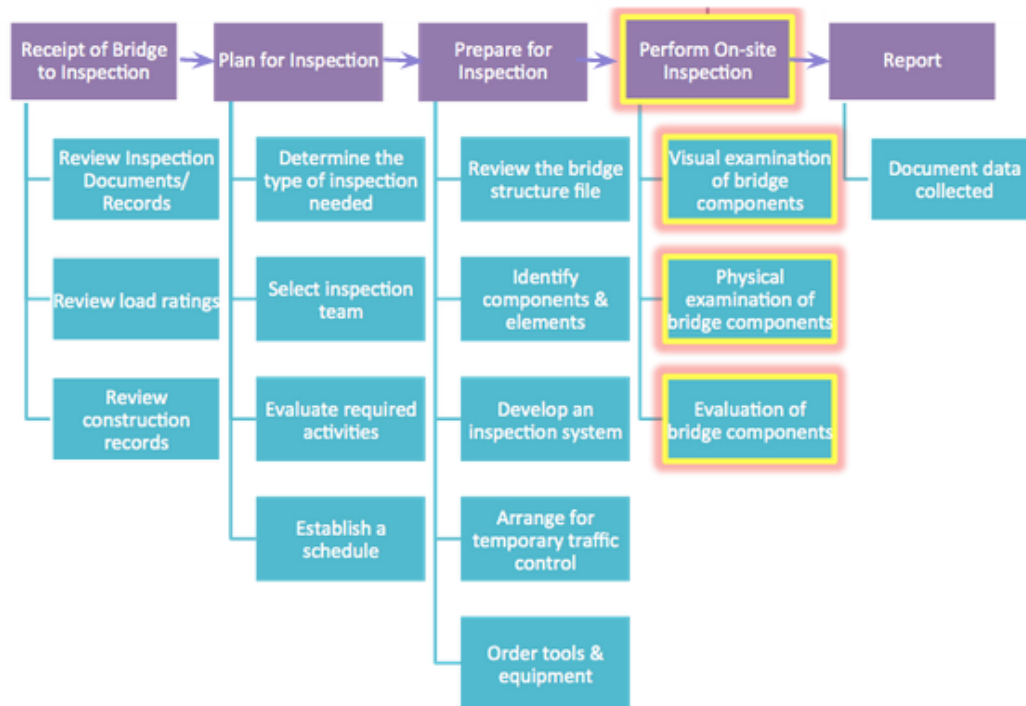


Figure 7: General Bridge Inspection Procedure

The bridge inspection process starts when an inspector is informed about a bridge that needs to be inspected. The inspector gathers any historical data about the bridge that needs inspection. The inspector visits the site to determine the equipment needed for inspection and places a reservation for the equipment. Afterwards, the inspector coordinates with the traffic controller for the bridge inspection on a certain date for safety precautions [1].

The FHWA administers the process and regulates it through a manual bridge inspection. On average, 2 to 3 inspectors do inspections in a day; however, it varies depending on the complexity of the bridge and its length [9]. Each part of the bridge is inspected and rated by an inspector for the parts of highest shear and moment. The four main parts are the deck of the bridge, truss, superstructure, and substructure. These parts are rated subjectively according to the Bridge Inspector's Reference Manual. Depending

on the rating of the condition, an action is taken. The rating varies from good condition, replacement or repair order or ultimately closing the bridge [1].

The inspectors record the data obtained during the inspection and store it once they return to the base. After the inspection process has finished and the data has been stored, the maintenance personnel have to follow the records collected to repair or replace the parts of the bridge, if necessary. The bridge inspection is an ongoing process therefore, despite the fact that they are inspected every two years, every year they inspect half the bridges thus, the system never becomes idle [1].

A sample inspection sequence for a bridge inspection is presented in Figure 8. It is imperative to develop a sequence for the inspection since it ensures safety and thorough inspection of the bridge.

<p><b>1) Roadway Elements</b></p> <ul style="list-style-type: none"> <li>➤ Approach roadways</li> <li>➤ Traffic safety features</li> <li>➤ General alignment</li> <li>➤ Approach alignment</li> <li>➤ Deflections</li> <li>➤ Settlement</li> </ul> <p><b>2) Deck Elements</b></p> <ul style="list-style-type: none"> <li>➤ Bridge deck: top and bottom</li> <li>➤ Expansion joints</li> <li>➤ Sidewalks and railings</li> <li>➤ Drainage</li> <li>➤ Signing</li> <li>➤ Electrical-lighting</li> <li>➤ Barriers, gates, and other traffic control devices</li> </ul> <p><b>3) Superstructure Elements</b></p> <ul style="list-style-type: none"> <li>➤ Primary load-carrying members</li> <li>➤ Secondary members and bracings</li> <li>➤ Utilities and their attachments</li> <li>➤ Anchorages</li> <li>➤ Bearings</li> </ul>	<p><b>4) Substructure Elements</b></p> <ul style="list-style-type: none"> <li>➤ Abutments</li> <li>➤ Piers</li> <li>➤ Footings</li> <li>➤ Piles</li> <li>➤ Curtain walls</li> <li>➤ Skewbacks (arches)</li> <li>➤ Slope protection</li> </ul> <p><b>5) Channel and Waterway Elements</b></p> <ul style="list-style-type: none"> <li>➤ Channel profile and alignment</li> <li>➤ Channel streambed</li> <li>➤ Channel embankment</li> <li>➤ Channel embankment protection</li> <li>➤ Hydraulic opening Fenders</li> <li>➤ Water depth scales</li> <li>➤ Navigational lights and aids</li> <li>➤ Dolphins</li> <li>➤ Hydraulic control devices</li> </ul>
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Figure 8: Sample Sequence for Bridge Inspection [1]

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## **1.5.1 On-site Bridge Inspection Process**

In order to perform an on-site inspection, the bridge components must be visually and physically examined and evaluated. During the inspection a thorough record keeping of all the inspected components of the bridge is done, especially if any deficiencies are found. However, the parts inspected vary depending on the complexity of the bridge. Nonetheless, all components of the determined bridge must be inspected.

First, the components are visually examined by inspecting for all noticeable failures by eyesight and prior experience. Then these failures are physically inspected with the use of equipment. For instance, some cracks can be visibly seen and later physically inspected to determine and record the type, the width, the length, and the location of the crack. During the visual inspection, picture taking is a common method used in order to refer back to where these failures were found and how severe they appear. During the physical examination, other equipment or tools are used for inspection. For example, hammers or chains are used in order to inspect for delamination or hollow zones [1]. Nonetheless, the on-site inspection requires all components of the bridge to be both visually and physically examined and evaluated.

### **1.5.1.1 Evaluating the Condition of a Bridge**

As these components are evaluated during the on-site inspection, inspectors rate the condition of these components based on a rating criteria set by the Bridge Inspector's Reference Manual (Fig. 9). This method relies on the experience of the inspectors as they evaluate the components of the bridge based on a scale ranging from 0 to 9. The rating of 0 to 4 classifies the condition of the bridge as structurally deficient or poor condition, whereas the rating of 5 to 9 ranges from fair to excellent condition [1]. This method is subjective, questioning if another system may improve the quality or reliability of the inspection process by allowing the rating of the condition of these components to be based on objective results.

<u>Code</u>	<u>Description</u>
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION - structural elements show some minor deterioration.
5	FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.
4	POOR CONDITION - advanced section loss, deterioration, spalling or scour.
3	SERIOUS CONDITION - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.
2	CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.
1	"IMMINENT" FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.
0	FAILED CONDITION - out of service - beyond corrective action.

Figure 9: Bridges Inspectors Rating Criteria (BIRM) [1]

## 2.0 Stakeholder Analysis

A stakeholder is a group, organization, member or system who can be affected by a system. The primary stakeholders of the bridge inspection systems are the Federal Highway Administration (FHWA), District Department of Transportation (DDOT), Bridge Design Engineers, Bridge Construction Team, and the Inspection Team which are directly involved with the construction and inspection of the bridge. The secondary stakeholders are groups of people that are not directly involved with the construction and inspection but are impacted indirectly such as the traveling public or the Bridge Users.

## **2.1 Primary Stakeholders**

### **2.1.1 Federal Highway Administration**

The Federal Highway Administration (FHWA) is an agency within the U.S Department of Transportation established in 1966 that supports State and local governments in the design, construction, and maintenance of the Nation's highway system and various federally and tribal owned lands. Through financial and technical assistance to State and local governments, the Federal Highway Administration is responsible for ensuring that America's roads and highways continue to be among the safest and most technologically sound [11]. Therefore, FHWA's main aim is to improve safety, mobility, and livability, and to encourage innovation.

### **2.1.2 Department of Transportation**

Department of Transportation (DOT) serves the U.S. by ensuring a fast, safe, efficient, accessible and convenient transportation system that enhances the quality of life for residents and visitors by ensuring that people, goods, and information move efficiently and safely [12]. Specific DOTs are involved in the planning, designing, construction, and maintenance for the states streets, alleys, sidewalks, bridges, traffic signals, and street lights. Also managing and making improvements to the street system to facilitate traffic flow through the state.

### **2.1.3 Design Engineers**

Designers and engineers include the groups that design the entire system providing a cost effective solution that minimizes time. The designers are responsible for the design of the bridge that needs to be constructed. Their main objective is to design a strong and light bridge that provides safety and longevity.

### **2.1.4 Construction Team**

The construction team includes the contractors who are responsible for building and constructing bridges that are safe for the travelers.

### **2.1.5 Inspection Team**

The inspection team includes the Inspecting Engineers, the managers and the contractors who detect the defected parts and areas of the bridge. The inspection team monitors the bridge at intervals and detects any defective parts for safety. There are two different types of inspectors. The team leaders who are experienced specifically for these inspections and the general inspectors that are trained due to insufficient amount of inspectors. Team leaders receive a minimal salary wage whereas the general inspectors may get paid in an hourly rate. Their main objective is to provide safety through inspections, minimize inspection time and cost and maximize their pay.

## **2.2 Secondary Stakeholders**

### **2.2.1 Bridge Users**

The bridge users include the passengers, commuters and any transporting goods. They are not directly involved in the inspection or construction of these bridges, nonetheless, the bridge partial shutdown for these inspections or maintenance extends their travel time.

## **2.3 Stakeholder Interactions**

The engineering design of the system, as illustrated in Figure 11, starts with the owner or DOT hiring a consulting engineering company to design the desired bridge. The design engineers then design the bridge and sends it back to the owner. The owners of the bridge then bid the bridge project to contractors, tell them the plan and sends them the

bridge design to have the bridge built. The contractors bid competitively, and the winning contractor constructs the bridge. After the construction of the bridge, the owners hire inspection engineers and contractors to inspect the bridge [13].

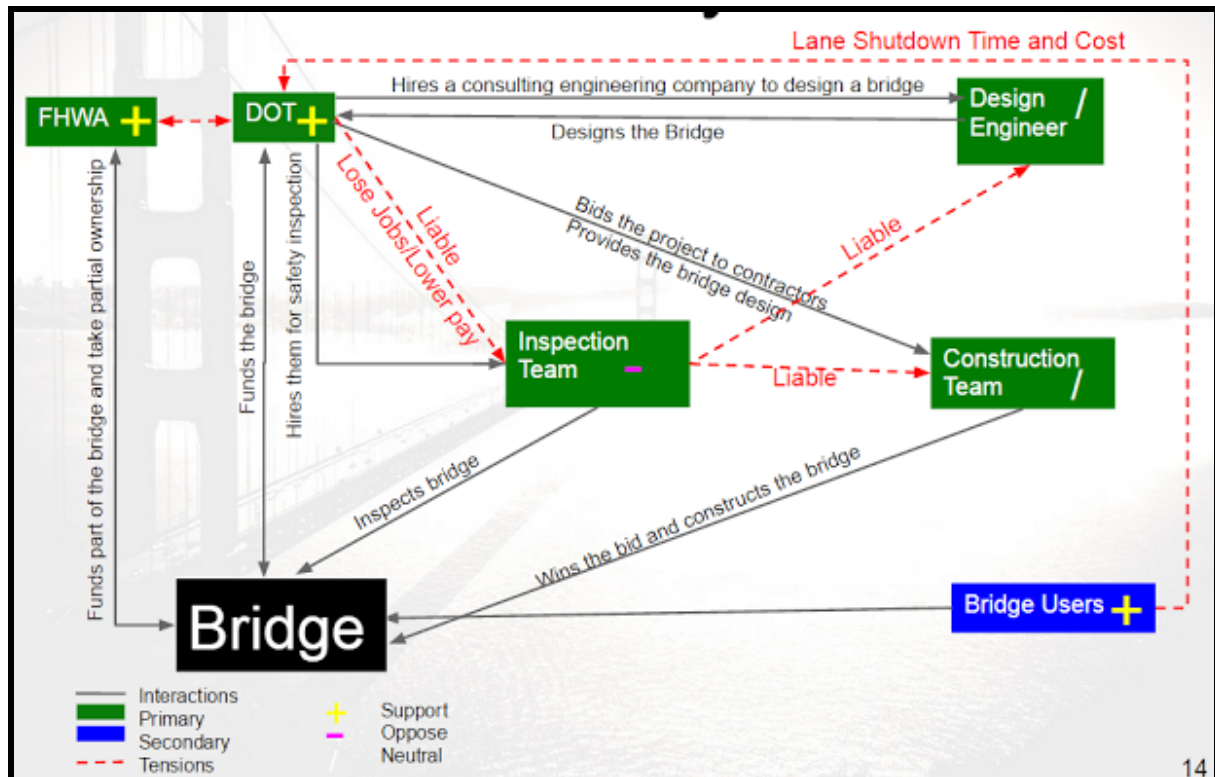


Figure 11: Stakeholder Interactions (grey) and Stakeholder tensions (red)

## 2.4 Stakeholder Tensions

There are several tensions that arise amongst the stakeholders involved in the bridge inspection system due to their differing objectives. As depicted in Figure 11, based on the objectives we can see that both FHWA and DOT would support an alternate bridge inspection system which would reduce the costs and assure public safety. This alternate system would eliminate traffic congestion caused by the closure of lanes which ultimately dissatisfied bridge users. The bridge users support the inspection, restoration, and protection of the bridges; however, as previously stated they disagree with the current



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process of closing lanes. An alternate inspection system that does not involve manual inspection and contribute to traffic congestion would be highly favored by bridge users.

Although the bridge designers and the Construction team are not directly affected there are some tensions due to the fact that the inspection team can hold the designers liable if the bridge were to not behave the way it was designed to behave or if the bridge was not constructed properly [13]. On the other hand, the inspection team would oppose an alternative bridge inspection system since it would eliminate manual labor and thus the need for these inspectors. This would either result in job losses or major financial concerns for the inspectors. Furthermore, the inspection team could also be held liable by the department of transportation if something on the bridge was not inspected correctly. These tensions between the stakeholders define our problem and present a need for an alternative system.

## **3.0 Problem and Need Statements**

### **3.1 Problem Statement**

Bridges play a key role in the national transportation system, and the ability to assess their condition is vital for safe transportation operations. Therefore, the FHWA requires the evaluation of all bridges, however, the bi-annual inspection cost is \$ 2.7 billion in the U.S. alone. The time required for the on-site inspection ranges from 1 to 3 days which involves the closure of lanes for the span of the inspection causing traffic congestion. These lane closures are required for both the safety of the inspectors and due to the size of the equipment which are essential in order to identify, and classify any deficient parts of the bridge.

The current inspection process relies on the experience of the inspectors as they evaluate the components of the bridge based on a scale ranging from 0 to 9 as previously stated, making the rating of inspection subjective. As time passes by and the frequency of use of bridges increases so does the fatigue damage of the deteriorating bridge

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infrastructures. Leading to the increase demand of inspecting these bridges prior than the 2-year period increasing the inspection cycle to a range of 6 months to a year that ultimately increases the bi-annual inspection cost for the U.S.

### **3.2 Need Statement**

There is a need for the FHWA to improve the effectiveness of the current bridge inspection process. The FHWA needs to reduce the total inspection cost by eliminating traffic control cost, and reducing both labor and equipment cost. The frequency of inspection, detection, and prevention of deficiencies needs to increase in order to prevent any hazardous damage of bridge failures as has previously occurred. Moreover, there is a need to remove the safety risk of personnel in a bridge inspection. The quality of the bridge inspection should increase by making the bridge inspection rating of the pass/fail criterion objective. Investing time and money in suitable alternative system will allow the FHWA to reduce costs, as well as time in the future. An effective, faster, and durable system not only reduces the costs but also prevents incidents such as the Tacoma Narrows Bridge.

## **4.0 System Requirements**

The requirements of this system were derived from the statement of need in order to eliminate the stakeholder tensions. The prominent objective is to reduce the cost and time of inspection, while maintaining and/or increasing the quality of inspection by making it objective and safe for users.

The Mission of the Bridge Inspection System (BIS) is that:

<b>Mission Requirements</b>	<b>Design Goal</b>
1. BIS shall reduce cost	< \$4,500
2. BIS shall reduce time of inspection	4 hours
3. BIS shall be safe for users	<16 failures (Range of 14 years)
4. BIS shall be objective	Quantitative results

<b>Functional Requirements</b>
BIS shall inspect all bridge components
BIS shall categorize the components according to the pass/fail criterion
The pass/fail criterion shall allow the components to be classified into a repaired, and/or replaced category
BIS shall store the data acquired onto the ground base

## 5.0 Proposed Solutions

### 5.1 Operational Concept

<b>Material</b>	<b>Type of failure</b>	<b>Inspection Method</b>	<b>Percentage to cause failure</b>	<b>Proposed Detection Method</b>
<b>Metal</b>	Cracking	Visual/Physical		<b>Vibration Analysis</b>
	Fatigue (less stiff)	Physical	13.05%	
	Corrosion (Loss of mass)	Visual/Physical	3.26%	
	Bending	Visual		Image Capturing device
	Missing connection	Visual/Physical		<b>Vibration Analysis</b>
<b>Concrete</b>	Section loss	Visual/Physical	20.65%	
	Structure crack at critical point (ex: Fracture critical...)	Visual/Physical	16.3%	
	Severe deterioration	Visual	2.17%	Image Capturing device

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Figure 11: Operation Concept of Proposed Detection Method

Figure 11 shows the different types of failures that have the highest percentage to cause a bridge failure can be inspected by the proposed detection method of vibration analysis.

## 5.2 Structural Vibration

All bridges undergo some form of dynamic loading, which cause them to vibrate. Bridges have always been subjected to dynamic influences due to vehicles driving over them. These dynamic influences can lead to deterioration of the bridge caused by the rapid growth of highway transportation. The dynamic loading that all bridges undergo vary from the forces of the bridge structure, to the car engine of the vehicle on the deck of the bridge, to the external forces/vibrations caused by the weather such as the wind.

Structural vibration is a repetitive motion that can be measured and observed in a structure, which can help characterize the behavior and performance of the structure as it responds to vibrations or dynamic loading. Unwanted vibration can cause fatigue or degrade the performance of the structure. Therefore it is desirable to eliminate or reduce the effects of vibration. However, in other cases, vibrations are unavoidable and sometimes even desired helping decipher what the changes in vibration mean. Understanding the effect on the structure is essential in order to control and modify the vibration or if necessary to minimize the structural response.

There are four methods of analyzing vibrations, which include free, forced, sinusoidal, and random vibration. The free vibration is the frequency at which the structure wants to naturally vibrate at. It is the natural response of a structure to some impact or displacement. The response is completely determined by the properties of the structure, and its vibration can be understood by examining the structure's mechanical properties. The forced vibration is the response of a structure to repetitive forcing function that causes the structure to vibrate at the frequency of the excitation. Sinusoidal vibration causes the structure that is excited by the forcing function to vibrate at a pure

tone with a single frequency such as a waveform. Finally, random vibration is composed of a complex combination of external forces applied to the structure.

The concept of this proposed system is using the vibration that the bridge exhibits through different external forces to predict the condition of the bridge. Each bridge is unique in its vibration; this uniqueness comes from the mass of the bridge, the stiffness of its components, the material that the bridge is built from and other parameters that are specific to each bridge such as its shape, length and number of lanes. Other dynamic influences occur due to the traffic that goes on the bridge having an effect on the vibration of the bridge.

Any change in the structure of the bridge will have an impact on that vibration of the bridge; the cause of this change could be due to a deficiency. Knowing that the deficiency will cause a change in vibration allows the bridge to be inspected with this method as it detects the condition of the bridge from the change in vibration. However, the changes in frequency vary allowing the detection of what parameter is actually being affected to be known. For instance, Figure 12 shows the red line to be the natural frequency obtained from the free vibration analysis method, whereas the blue line demonstrates a phase shift to the left stating that the stiffness of the structure has decreased. However, if the phase shift had been to the right it will show that the structure has become stiffer. Thoroughly analyzing these diagrams is a prominent concern in order to identify the condition of the bridge structure.

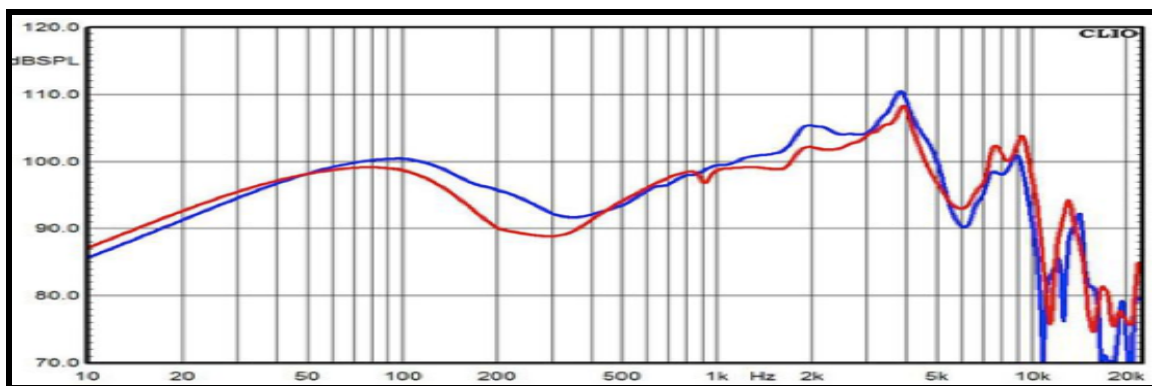


Figure 12: Natural Frequency (red) vs. Phase Shift (blue)

## 5.3 Accelerometers

Electronic sensors that convert vibration motion into electrical signals can measure structural vibrations. Electronic motion sensors are devices that detect when the original condition has changed. The sensor has a normal state and reports when the standard status is disturbed. A considered alternative is accelerometers, which is an electromechanical device that measures vibration or acceleration forces. Accelerometers designed to measure vibration are based on the piezoelectric effect.

Piezoelectric accelerometers are used when a mass applies force (pressure) to a nonconducting material creating a high-impedance charge resulting in a voltage across the material (Fig. 13). Essentially, this effect generates an electrical output that is proportional to the applied acceleration generating an opposed buildup of charged particles on the piezoelectric material. This charge is proportional to the applied force. This applied force alters the alignment of positive and negative ions, which results in an accumulation of these charged ions on opposed sides. Accelerometers obey Newton's law of motion,  $F=ma$ . Therefore, the total amount of accumulated charge is proportional to the applied force, and the applied force is proportional to acceleration.

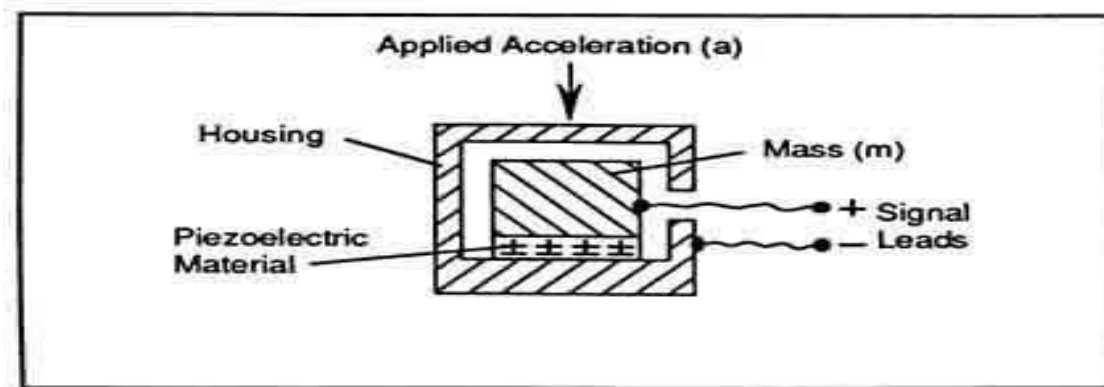


Figure 13: General Accelerometer Dynamics

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Some requirements for accelerometers are current excitation, AC Coupling, Grounding, Filtering, and Dynamic Range. The current excitation is the external current needed to power the amplifier. This is necessary when choosing a data acquisition system since one needs to know the excitation voltage the accelerometer requires or the excitation may not be sufficient for the accelerometer to work. The accelerometer requires AC Coupling since it acquires a signal from both the direct current (DC) and alternating current (AC) where the DC portion offsets the AC portion from zero. The AC Coupling removes the DC offset by having a capacitor in series with the signal. This eliminates the long-term DC drift that sensors have due to age and temperature effect, increasing the resolution and the usable dynamic range of the system.

Another requirement is properly grounding the system due to the fact that vibration measurements are highly susceptible to noise especially in an electrically conductive surfaces allowing noise to enter the ground path of the measurement signal through the base of the accelerometer. One can avoid improper grounding by grounding either the signal conditioning input or the sensor but not both. If the sensor is grounded, it must connect differentially. If the sensor is floating, the signal conditioning systems should be connected inverting input to ground.

Adding a low-pass filter is also required since it reduces signals with frequencies higher than the cutoff frequency and passes signals with a frequency lower than the certain cutoff frequency. This identifies the correct range of frequencies required not allowing samples that distort the measurement. Compliant materials, such as a rubber interface pad, can create a mechanical filtering effect by isolating and damping high-frequency transmissibility. Here is where the frequency range is established. The last requirement is a dynamic range, which is a measure of how small you can measure a signal relative to the maximum input signal the device can measure, expressed in decibels. Thus, the input range and the specified dynamic range are important for determining the needs of the system.

Choosing an accelerometer that complies with the above requirements will allow accurate data to be collected when incorporating them for our bridge inspection process.

---

There are two potential design alternatives. The first proposed alternative involves installing these accelerometers mounted onto the bridge with cables that will serve as both a power source and a communication system. Consequently, the second proposed design alternative consists of mounting these sensors connected to a low power communication system that will transport the acquired data to a transportable device capable of taking the collected data from the bridge site to the ground base station.

However, we must first identify the optimal location to place these accelerometers. The most suitable location will vary per bridge due to its complexity. Nonetheless, incorporating these electronic sensors in these certain parts of the bridge will help analyze if any part inspected has changed from its original state and if so, by how much, stating the level and type of the vibration. This will allow us to know if these parts of the bridge are deficient since the accelerometer will be modified to a particular specified range allowing us to see any variation in its condition. The level of variation according to its recorded previous condition would allow us to quantify the change and ultimately evaluate if the inspected part needs to be repair, replaced, restored or ultimately left unchanged.

## **5.4 Proposed Alternatives**

### **5.4.1 Manual Bridge Inspection**

As previously stated, the current process is a manual inspection process which can be seen in the Figure 16. An advantage for this process is the fact that inspectors are comfortable with this process and the quality of inspection is said to be 95% reliable [9]. However, this method involves manual labor incurring costs, it is time consuming, and hazardous for the personnel.



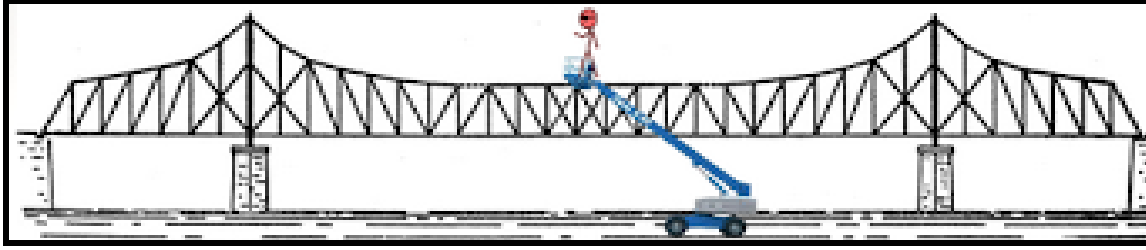


Figure 16: Manual Inspection

### 5.4.2 Mounted Sensors with Cables

The alternatives of the proposed system will depend on the vibration analysis of the bridge, by which the area of deficiency is detected and will be examined. The proposed solution is to place the accelerometers at critical points of the bridge with a certain distance that will cover and measure frequencies of the whole bridge. If a deficiency occurs around or in the area that the accelerometer is placed, it is more susceptible to be detected. Finding the source of the error, narrows the area of search to a certain focused area.

Specifically, the first inspection design is using accelerometers with cables as shown in Figure 17. As mentioned previously, the accelerometers can be placed on the bridge ensuring coverage for all areas and components of the bridge. The distance at which these accelerometer will be placed can be determined by the range of data transmission for a specific accelerometer. These accelerometers can be placed at critical points on the bridge such as the the areas with high moment since that is where a deficiency is more likely to happen. After the accelerometers are placed, they will need to be powered to operate. A solution is to put a cable that is connected to a power source through all the accelerometers to supply that power.

Additionally, we will also need a method for data collection. This communication of data can be accomplished through an additional cable. A second cable can run through the accelerometers connected at the end to Data Acquisition Unit (DAU) where all the data will be stored. Analyzing the data will give the condition of the areas that were inspected. If the condition obtained shows any deficiency, an image-capturing device will be used by personnel to capture imagery data for these areas. These images will be

analyzed according to the pass/fail criterion to decide the ultimate condition of the inspected component.

An advantage of this design is that it is easy to install and allows for fast power supply and data transmission. However, installing cables requires many accessories such as clamps, tapes, and adhesives for secure connection which increases the cost [4]. Furthermore, another shortcoming of this method is that using accelerometers will require the inspectors to acquire new technological skills to be able to interpret the data gathered.

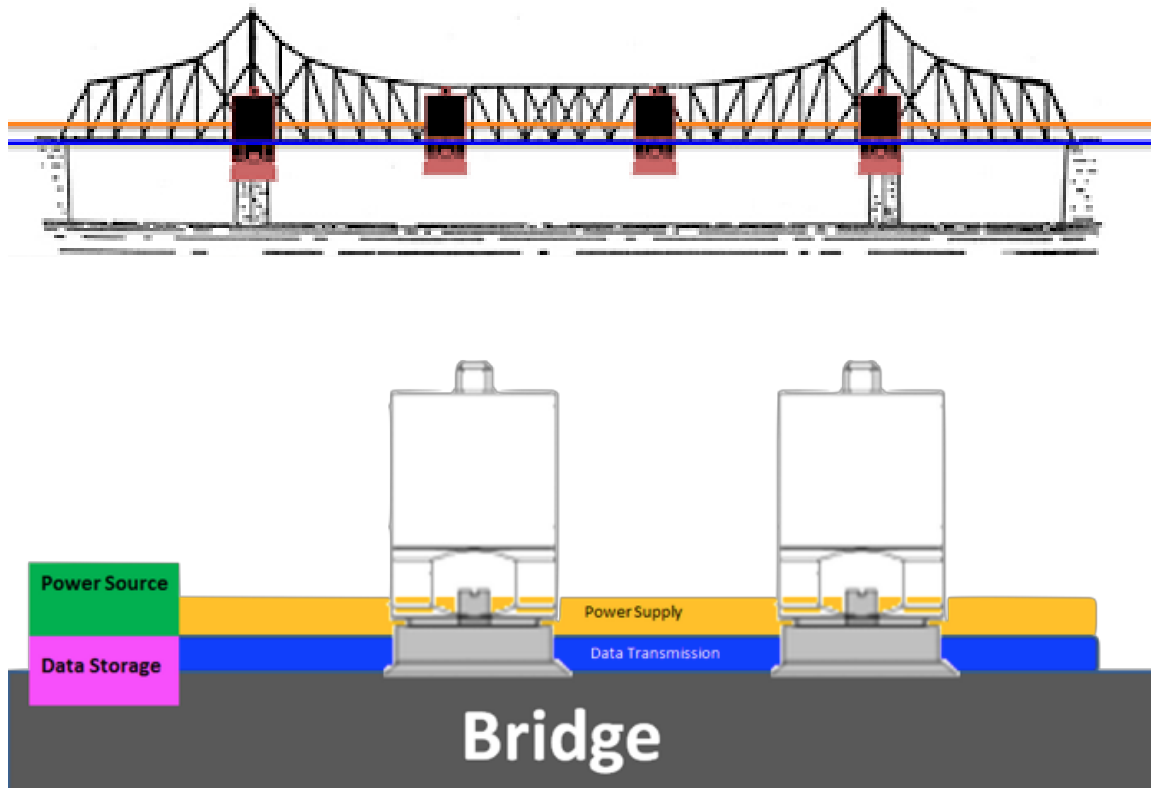


Figure 17: Design alternative using sensors and cables.

#### 5.4.3 Mounted Sensors connected to Low-Power Communication System and the use of a Transportable Device (UAV)

The second design alternative consists of using sensors with a low power communication system and an unmanned aerial vehicle as shown in the figure 18 and 19. The concept for this design is the same as the concept of the first design alternative however, in this case the cables for power and communication will be replaced by battery

power and the communication between the devices will be wireless. This alternative will not require DAU, nonetheless, the data from all the accelerometers will be collected at one node and transferred to a flying UAV that collects and transport the data for analysis. Afterwards, the UAV takes Imagery data of these areas for analysis. Based on the data collected (vibrations and images), the condition of the bridge is determined.

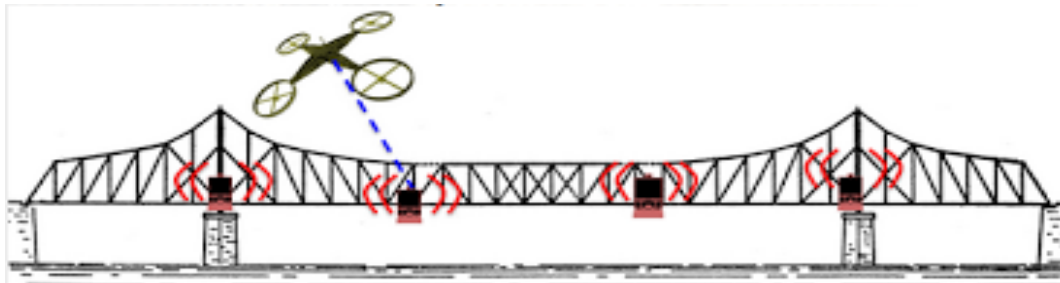


Figure 18: Overview of Bridge Inspection System design with sensors, low power communication system, and UAV

This alternative includes a communication system that will transmit the information to a vehicle that will collect that data. For this design, we will need to mount the accelerometers onto individual microcontrollers that will provide power and data transmission. As shown in figure 19, the microcontrollers have batteries for power supply, antennas for communication, and a memory storage to store the frequency data from the accelerometers. These sensors will then form a wireless sensor network which is a network of spatially connected sensors that monitor physical or environmental conditions [14]. The accelerometers on the bridge will communicate with each other through the antennas and send their data down to a main accelerometer. That accelerometer will then communicate to another microcontroller placed on a UAV flying by and transmit all of the information.

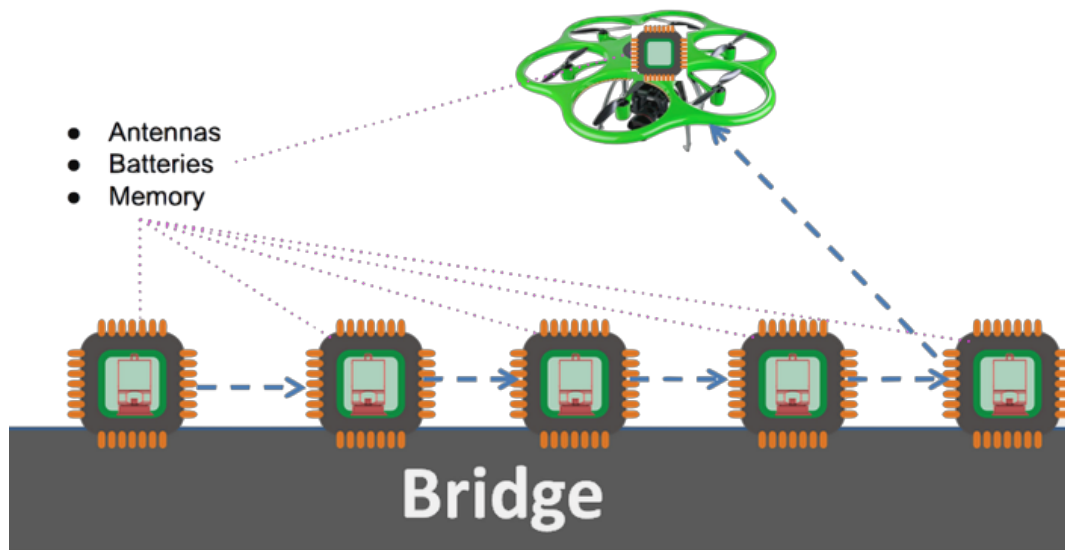


Figure 19: Accelerometers, Microcontrollers, and UAV for the design alternatives.

This design alternative is safe for the inspecting personnel as they will not have to physically go around the bridge to collect data. This method also provides quick real time data through the antennas as it is all a part of the network. However, some of the major shortcomings of this alternative is that it also, like the first design alternative, requires the inspectors to acquire new skills. Another concern, is that the integrity and security of the data is questioned since it is all part of a network.

## 6.0 Method of Analysis/Simulation

### 6.1 Method of Analysis

The method of analysis consists of three main models: vibration analysis model, life cycle cost model, and utility model.

The vibration analysis model involves several inputs. These inputs are the factors required to examine the behavior and condition of the bridge structure as it responds to

these parameters. Each bridge is unique in its vibration due to the forces of its own structure. This uniqueness comes from the mass of the bridge, the stiffness of its components, the material that the bridge is composed of, its shape, length, load capacity and number of lanes. Other input factors involve the mass and velocity of cars driving on the bridge structure exerting pressure, fluctuations in acceleration, and external random vibrations that may be caused by the structure, vehicles, the sensors themselves or other extraneous factors.

The electronic sensors used to analyze vibrations will output these vibration motions into electrical signals displayed in various diagrams. By analyzing the electrical signals, one can understand the nature of the vibration. Signal analysis is generally divided into time and frequency domains; each domain provides a different view and insight into the nature of the vibration. Time domain analyzes the signal as a function of time. The plot of vibration versus time provides information that helps characterize the behavior of the structure. Its behavior can be characterized by measuring the maximum vibration or peak level, or by finding the period, or estimating the decay rate, which is the amount of time for the envelope to decay to near zero.

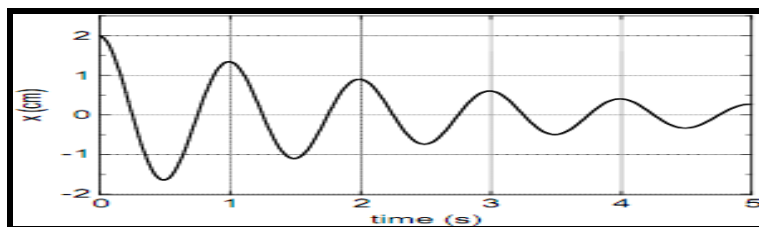


Figure 18: Structure responds with vibration plotted versus time

The above (Fig. 18) shows the mechanical structure responding to an impact with vibration plotted versus time. The line indicates the motion of the structure as it vibrates about its equilibrium point.

The frequency domain analysis transforms the time signals into the frequency domain called Fourier Transform. Fourier Transform theory states that any periodic signal can be represented by a series of pure sine tones.

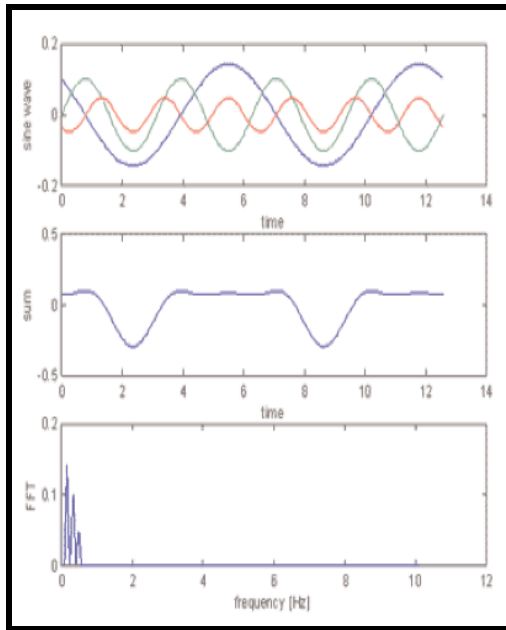


Figure 19: Limited number of sine waves

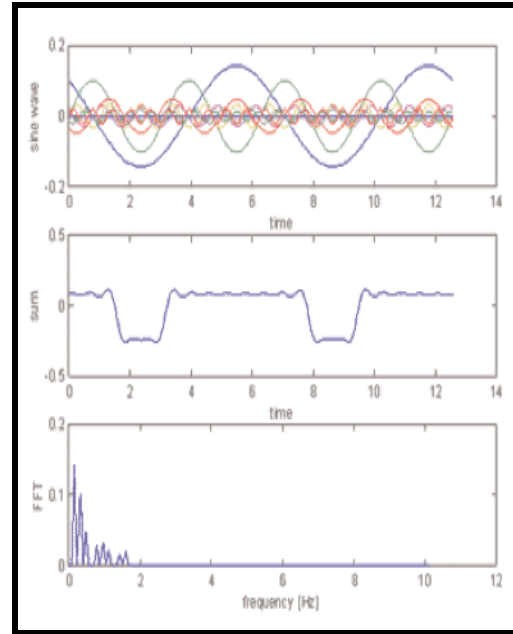


Figure 20: Improved number of sine waves

The figures above demonstrate how adding up a series of sine waves can create a square wave; each of the sine waves has a frequency that is a multiple of the frequency of the square wave. The amplitude and phase of each sine tone must be cautiously chosen in order to obtain the right waveform shape. When using a limited number of sine waves such as in Figure 19, the result resembles a ragged square wave. However, as more and more sine waves are added such as in Figure 20, the result essentially looks more like a square wave.

In both figures, the third graph shows the amplitude of each of the sine tones. In Figure 19, there are three sine tones which are represented by three peaks in the third plot. The frequency of each tone is represented by the location of each peak on the frequency coordinate in the horizontal axis. The amplitude of each sine tone is represented by the height of each peak on the vertical axis. In Figure 20, there are more peaks because there are more sine tones added together to form the square wave. This third plot can be interpreted as the Fourier Transform of the square wave.

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By analyzing these electrical signals, the nature of the vibration can be better understood. Therefore, the vibration analysis model will be capable of outputting the condition and performance of the components inspected in forms of electrical signals that will need to be further analyzed to describe the behavior of the results and characterize the condition of the structure.

The life-cycle cost of each proposed alternative will be dependent on the number of accelerometers and the accessories required. These will depend on the parameters of the bridge. The placement of accelerometers is imperative in order to obtain accurate data, for that reason accelerometers will be placed at the critical points on the bridge. These critical points vary from one bridge to the other. The parameters of a bridge that are essential for determining these critical points are the length of the bridge, the number of spans, the length for each span, the number of lanes, and the highest moments on the bridge. The highest moments are considered as critical points as they are highly susceptible to vibration and that will provide accurate signal with less noise than other points on bridge where the signal of the actual vibration might be more vulnerable to external noise.

Given these parameters for each bridge we will determine the number of accelerometers and accessories needed for that specific bridge, by which the cost of the life cycle inspection can be calculated for that specific bridge according to the design alternative. However, foreseen inherited cost associated with these proposed alternatives consist of acquisition, concurrent, and indirect costs. However, the life cycle cost will be later discussed in more thorough detail.

The utility of each alternative will be calculated using the attributes shown in Figure 21. These attributes are the importance of that feature to the inspection system. After rating each alternative to the attributes, the utility of each alternative will be calculated (Fig. 22).

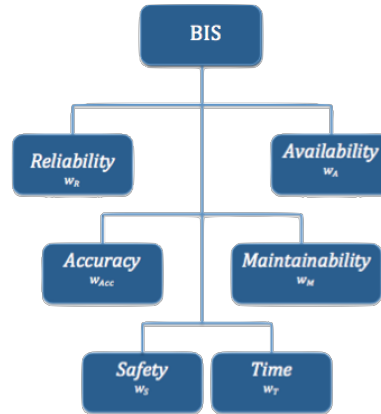


Figure 21: Attributes of Inspection System

		Reliability	Availability	Accuracy	Maintainability	Safety	Time	Utility
		$w_R$	$w_A$	$w_{Acc}$	$w_M$	$w_S$	$w_T$	
1	Manual	R1	A1	Acc1	M1	S1	T1	U1
2	Mounted w/ cables	R2	A2	Acc2	M2	S2	T2	U2
3	Mounted w/ UAV	R3	A3	Acc3	M3	S3	T3	U3

Figure 22: Utility for each alternative

$$Utility = w_R R + w_A A + w_{Acc} Acc + w_S S + w_M M + w_T T$$

Equation 1: Utility calculation



## 6.2 Simulation

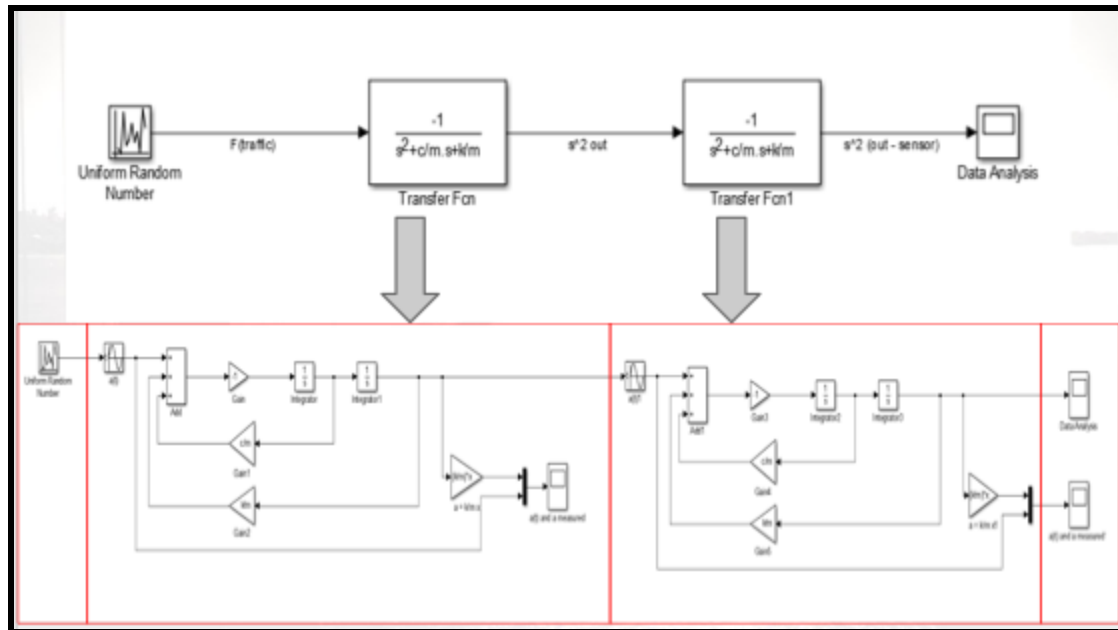


Figure 23: Simulation Design

The uniform random number generator will be used in order to replicate the external forces that bridges are exposed to due to the dynamic loading of cars driving over them. The first transfer function consists of the parameters of the bridge structure using the dynamics equation known as  $kx+c\dot{x}+m\ddot{x}$ . These parameters can help examine the behavior and condition of the bridge structure as it responds to the vibrations caused by the dynamic loading and other external forces.

The mass is represented by  $m$ , damping as  $c$ , and stiffness by  $k$  which correspond to the structure of the bridge. The replication of the external forces done by the number generator, applies other factors to the first transfer function or the bridge. This factors vary from the mass and velocity of the cars, the load capacity of the structure, time span of the pressure or dynamic loading, the length of the bridge, the number of lanes and load on them, the fluctuation in acceleration, and other external vibrations caused by the weather or any repetitive forcing function that might affect the excitation of the vibration. Altering the behavior or response of the output of the first transfer function.

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The second transfer function will receive the output obtain from the first transfer function. This transfer function uses the same dynamic equation since it is known to be the fundamental equation for accelerometers. Once it obtains the output of the first transfer function, without having any known parameters inputted manually it should output the same results. If so the use accelerometers will be an essential alternate inspection system.

However, the second transfer function will have some triggering factors included such as other external noise that may be caused by the mounting of the accelerometers, the sensor noise, if any sensor malfunction is occurring, how sensitive to noise the sensor us, the power source, and even if the performance of the sensor has changed.

Prior to the second transfer function, parameters will be changed both in the uniform random number generator and the first transfer function to see how the variations change the performance and behavior of the output frequencies. By having base variables that remain constant we can see how each parameter affects the results and ultimately correlate the effects to trends.

If we increase the mass, we will see the result of a lower natural frequency and vise versa. These trends can help analyze if the component or structure is behaving as it was designed to behave. By examining the results, we can determine the condition of the component by analyzing its behavior as it responds to vibrations.

## **6.3 Design of Experiment**

The input parameters will be varied in order to obtain an insight of the system and more specifically the condition of the bridge. Studying these changes in the output due to the varied parameters will give an understanding of how it relates to the change in the input. The amount of variation allows us to quantify the severity of the condition of the bridge according to change of the output.

These parameters will be modified by changing them to have a lower and upper bound apart from its base parameters to perform a sensitivity analysis on the behavior of the output. For instance, a larger stiffness will result in a higher natural frequency, and a

larger mass will result in a lower natural frequency. The chart below demonstrates the base parameters of the Theodore Roosevelt Bridges and its variation according to each factor (Fig. 24).

Input						Output
Length	# of Lanes	Value of (m)	Value (v)	Value of (k)	Value of (c)	Freq. Response
3,200 ft	4	S	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$
		M	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$
		L	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$
	6	S	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$
		M	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$
		L	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$
	8	S	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$
		M	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$
		L	L, M, H	$k_i: (k_1, k_2 \dots)$	$c_i: (c_1, c_2 \dots)$	$f(L, l, m, k, c)$

Figure 24: Design of Experiment

## 6.4 Cost Model for Theodore Roosevelt

The three alternatives are: manual, sensors with cables, and sensors connected to a low power communication systems and a transportable device. In order to have meaningful cost estimates, we will be looking at a 50 year life cycle of a bridge inspected every 2 years. The sample, Theodore Roosevelt Bridge, has a total length of 3200 ft containing 5 spans with 12 lanes in both directions. Figure 25 shows the costs for the different alternatives.

	Set (change every 10 yrs)					Concurrent	Indirect/person	Total (50 yrs)	
	Sensors	Installation	Accessories		Programming				
<b>Manual</b>	0	0	0	0	0	0	30,000	0	750,000
				<b>DAU</b>					
<b>Mounted w/ cables</b>	33,800	4,000	26,790	50,000		2,000	2,578	400	439,802
				<b>Batteries</b>	<b>UAV</b>				
<b>Mounted w/ UAV</b>	33,800	5,000	4,875	3,000	30,000	3,000	648	800	268,375

Figure 25: Cost for different design alternatives

The manual cost is estimated to be \$30k per inspection, which results in \$750k for the 50 years of inspection. For the design alternative of mounted sensors with cables, the optimal amount of sensors required for the inspection is 65 accelerometers costing \$33.8k. BDI accelerometers are chosen as a sample in this cost estimation. The cost of these accelerometers is \$520 per unit. The installation cost is estimated to be \$4,000 provided by BDI representative. The accessories include the cables used to wire the accelerometers for power and data transmission resulting in a cost of \$26.8k.

The Data Acquisition Unit (DAU) alone costs around \$50k. Another additional cost associated with this alternative is the labor cost required since inspectors will be needed if a deficiency is found in order to verify with visual inspection. During the visual inspection the use of an image capturing device will be needed for record keeping and analyzing of the data resulting in \$2.6k.

The following equations show how these costs were calculated for this alternative:

- Sensors = Number of spans \* Number of floor beams \* price of each accelerometer
- Accessories (cables) = number of cables \* length of bridge in ft \* price per ft
- Inspection cost = price of closing lane + price of equipment rental + (wage for 2)

The total cost for 50 years was calculated as follows:

- Total = (5\*cost for a set) + price of DAU + Programming + (25 \* Inspection cost) + indirect cost

The third design alternative is estimated to cost \$270k. These costs were calculated using the same method as the second alternative, however, with a higher installation cost of \$5,000. The accessories for this system are the communication system needed to transmit the data between accelerometers. In order for the accelerometers to communicate with each other, 3 additional micro-controllers will be placed to each accelerometer. The price for these microcontrollers is \$25 per unit. The price for the concurrent cost taken into account is the price of 2 inspectors working one full day as well as the battery change for the UAV each year having a cost of \$650 per inspection. The calculation for these costs were as follows:

- Accessories = Number of micro controller/acc.\* Number of spans \* Number of floor- beams \* price of each micro-controller
- Inspection cost = wage of 2 inspectors for a day + Battery change for UAV every 2 years
- Total = (5\*cost for a set) + price of UAV + Programing + Batteries to run acc. And micro-controller + (25 \* Inspection cost) + indirect cost

#### 6.4.1 General Cost Model for the DC Area

The District of Columbia has 199 bridges in total. From these bridges, 21 are rated as Structurally Deficient (SD) and 102 are considered to be Functionally Obsolete (FO) meaning that their condition is close to being poor. The SD bridges need to be inspected prior than the 2-year period, meaning that the frequency of inspection is more often. Knowing these facts we can calculate the inspections per year for the District area.

Total	SD	SD/FO
199	21	102
Insp. Every 2 years	178	76
Every year (normal)	89	38
Total Every year	110	161

Figure 26: Statistics for the bridges in the District of Columbia (DC)

From Figure 26 we can conclude that there are 110 bridges to 161 bridges that need to be inspected each year in the upcoming 50 years. The average cost per inspection is \$4.5k, therefore this calculation shows the total cost for an inspection life cycle of 50 years for the District of Columbia. Figure 27 shows the price ranges for each alternative over the next 50 years for the District of Columbia.

Total (50 yrs) AVG (DC)		
Manual	24,750,000	36,225,000
Mounted w/ cables	14,513,466	21,242,437
Mounted w/ UAV	8,856,375	12,962,513

Figure 27: Estimated Cost for the system design alternatives

## 7.0 Project Management

### 7.1 Budget Analysis

Our individual hourly rate is \$40.00 per hour, however, with the GMU overhead cost, which is a factor of 2, our total rate per person is \$80.00 per hour. We arbitrarily estimated the time to be spent on the project per week, for 38 weeks using as reference the time spent per week for the first 3 weeks into the project. The estimated time to be spent on the project is 1,779 hours with a total budgeted cost of \$142,320.00. We estimated a worst and best case scenario by choosing the probability to be 15 percent, giving us a 85 percent probability of reaching our estimated goal. As the project evolved

however, we've put more hours than was planned. The chart below shows the actual cost slightly on the same margin as our worst case scenario.

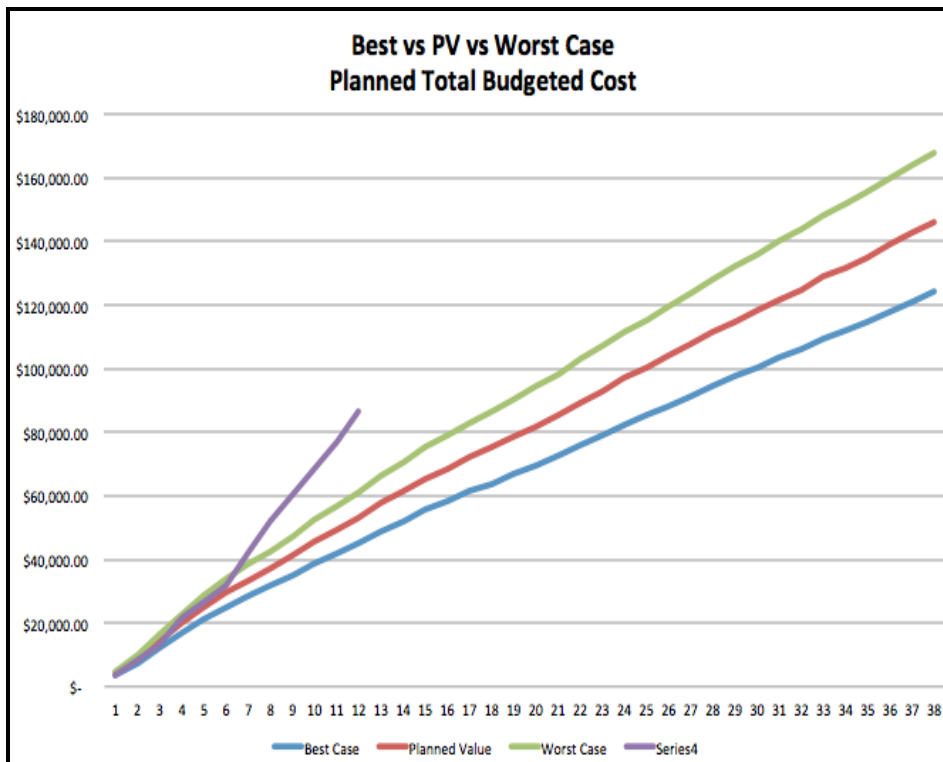


Figure 28: Budget Analysis

The SPI and CPI ratio shows that our schedule performance index is below 1, indicating that we are under schedule. The cost performance index demonstrates that we are above the projected cost. This ultimately shows that despite our time being spent on the project no process has actually been made. We need to be more productive leading to our set goal.

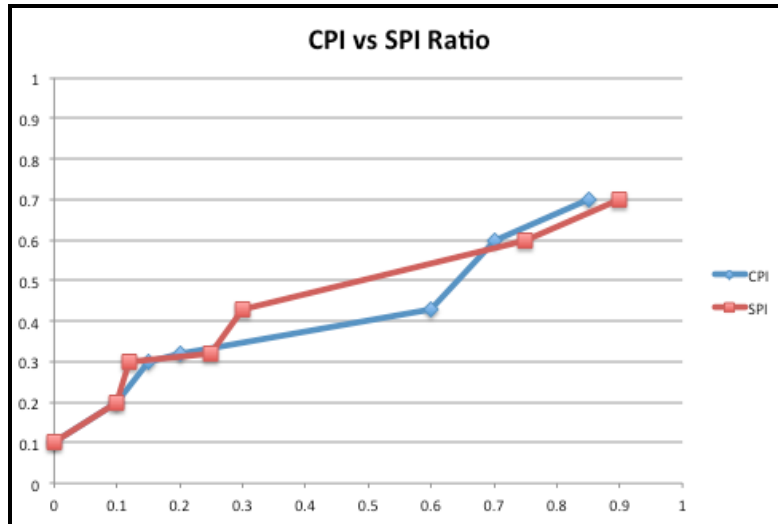


Figure 29: Cost Performance Index (CPI) vs. Schedule Performance Index (SPI)

## 7.2 Work Breakdown Structure

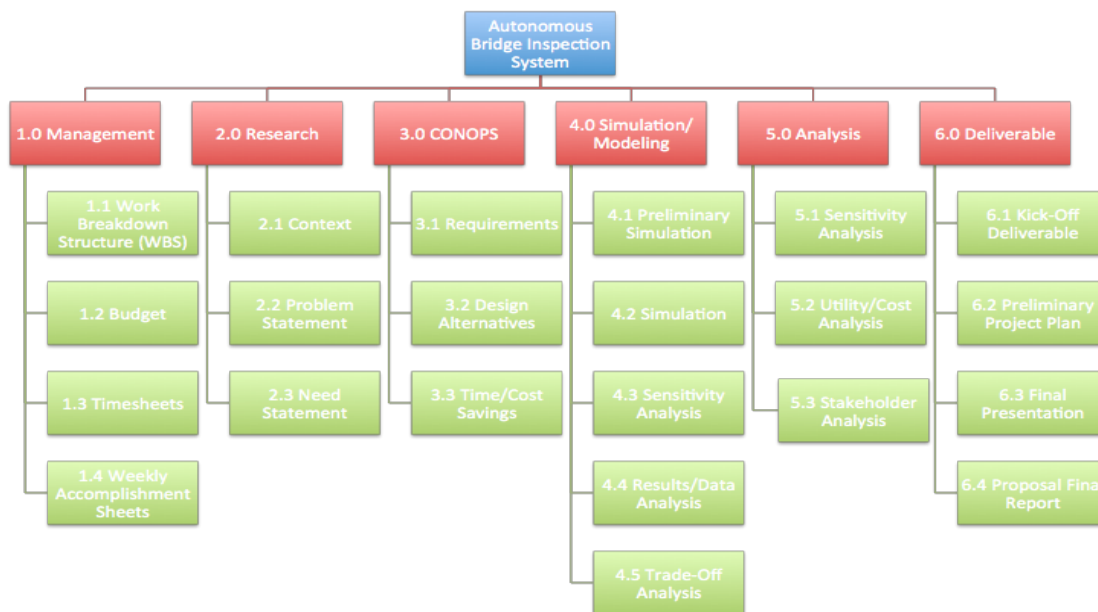


Figure 30: Work Breakdown Structure



## 7.3 Project Plan

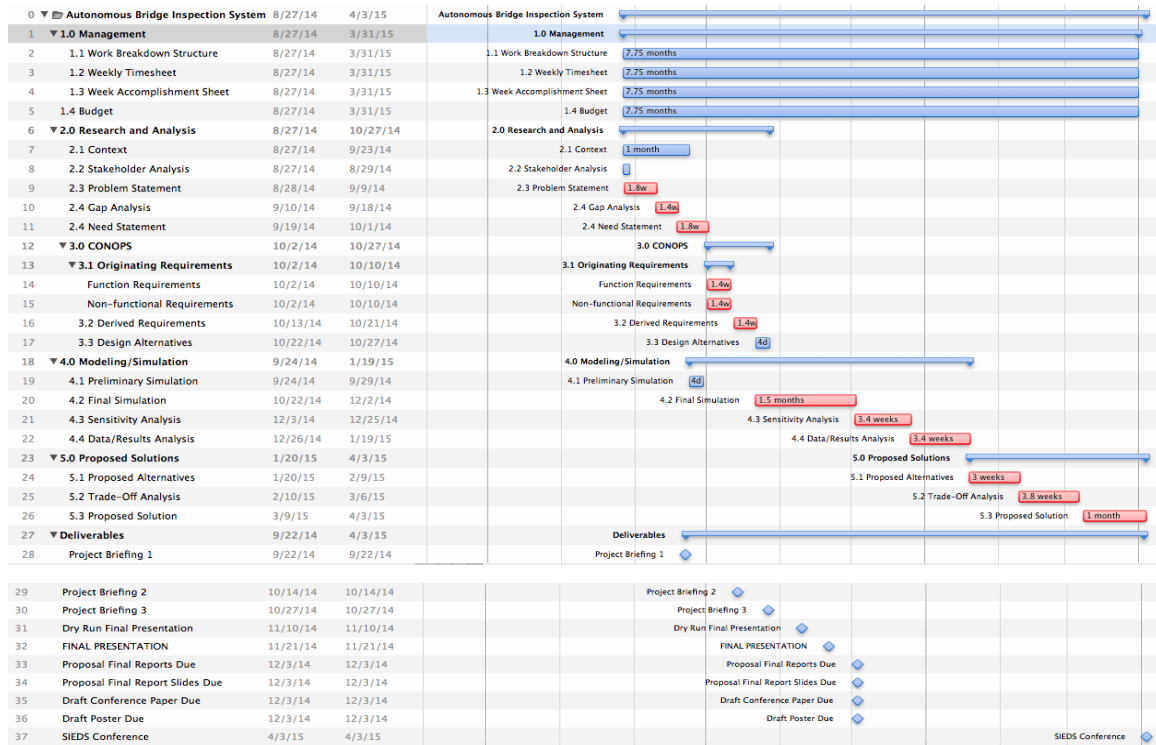


Figure 31: Project Plan

## 8.0 Risk/Mitigation

There are several risks associated with our project of designing an alternative bridge inspection system. Firstly, there is a risk with data collection due to the lack of accessible or/and accurate data required to fully know and understand our system. To mitigate this risk, we can make assumptions or use similar data from similar studies. Another major risk is reliability. Our proposed solutions may not meet the current reliability of the bridge inspection process. To mitigate this risk we will use the criteria currently used to replicate the bridge inspection process improving the quality of inspection by obtaining objective results which ultimately make the proposed system more reliable than the subjective rating of the current inspection process.

Furthermore, simulation poses a risk as the failure to complete the simulation on time could delay the whole project. Our mitigation strategy, was to start early and try to supplement more time as needed such as working over winter break. Lastly, there was a risk that we may be unable to fully understand the objectives of the stakeholder due to the lack of contact. We mitigated this risk by initiating contact with our sponsor, Virginia Department of Transportation and the Federal Highway Association to understand the concept of our system more thoroughly.

## **9.0 Future Plan**

Although the Fall 2014 semester is coming to an end, it is important that we continue working on our bridge inspection project to assure success. We will continue working on this project throughout winter break, occasionally holding meetings. Specifically, we will be working on our simulation, testing and results through winter break and throughout next semester. We will then meet with the advisors and professor at the beginning of the next semester to discuss our progress with them and receive feedback. We will then pick up the pace and continue working on the project as suggested by our advisor and professors.

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