Integrated Remote Sensing Technologies for Condition Assessment of Concrete Bridges

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ABSTRACT

INTEGRATED REMOTE SENSING TECHNOLOGIES FOR CONDITION ASSESSMENT OF CONCRETE BRIDGES

Salam Yaghi

Government reports and published research have flagged and brought to public attention the deteriorating condition of a large percentage of bridges in Canada and the United States. Inspection and rehabilitation programs are being implemented to monitor and maintain deteriorated bridge infrastructure. Current practices of bridge inspection and condition assessment rely heavily on visual inspection, limited basic testing such as hammer sounding and chain dragging, and the use of Non-Destructive Testing on ad-hoc basis. These methods suffer from several limitations including subjectivity and uncertainty of visual inspection process, as well as traffic disruption resulting from lane closure during inspection. This research aimed to study, evaluate, and experiment with the use of remote sensing technologies in bridge inspection to minimize drawbacks of current practice. To achieve this objective, two models are developed in this research. The first is a comparative study of remote sensing technologies for concrete bridge condition assessment that provides a systematic approach of selecting most suitable technologies for use in condition assessment. Seven remote sensing technologies are examined in this model. It recommends technologies to be implemented based on a set of flexible multi-attributed criteria. The model provides flexibility to select specific set of these criteria and to define their weights based on user preferences and project objectives. The second model proposes a hybrid system of remote sensing technologies to augment current practice in bridge inspection and eliminate some limitations such as minimizing traffic disruption while performing bridge inspection and enhancing inspection data analysis and visualization. The hybrid system integrates the use of thermal Infrared (IR) and Ground Penetrating Radar (GPR). These technologies have the ability of acquiring data from a distance which minimizes traffic disruption. Results obtained from IR and GPR are in the form of maps of the detected defects on the concrete bridge deck. These maps are used as input in ArcGIS for better representation, visualization, and reporting of the defects and their extents. The hybrid system was examined in a case study of a concrete bridge deck in the city of Laval, Montreal, Quebec, Canada. The results are compared to those obtained using hammer sound test for validation.

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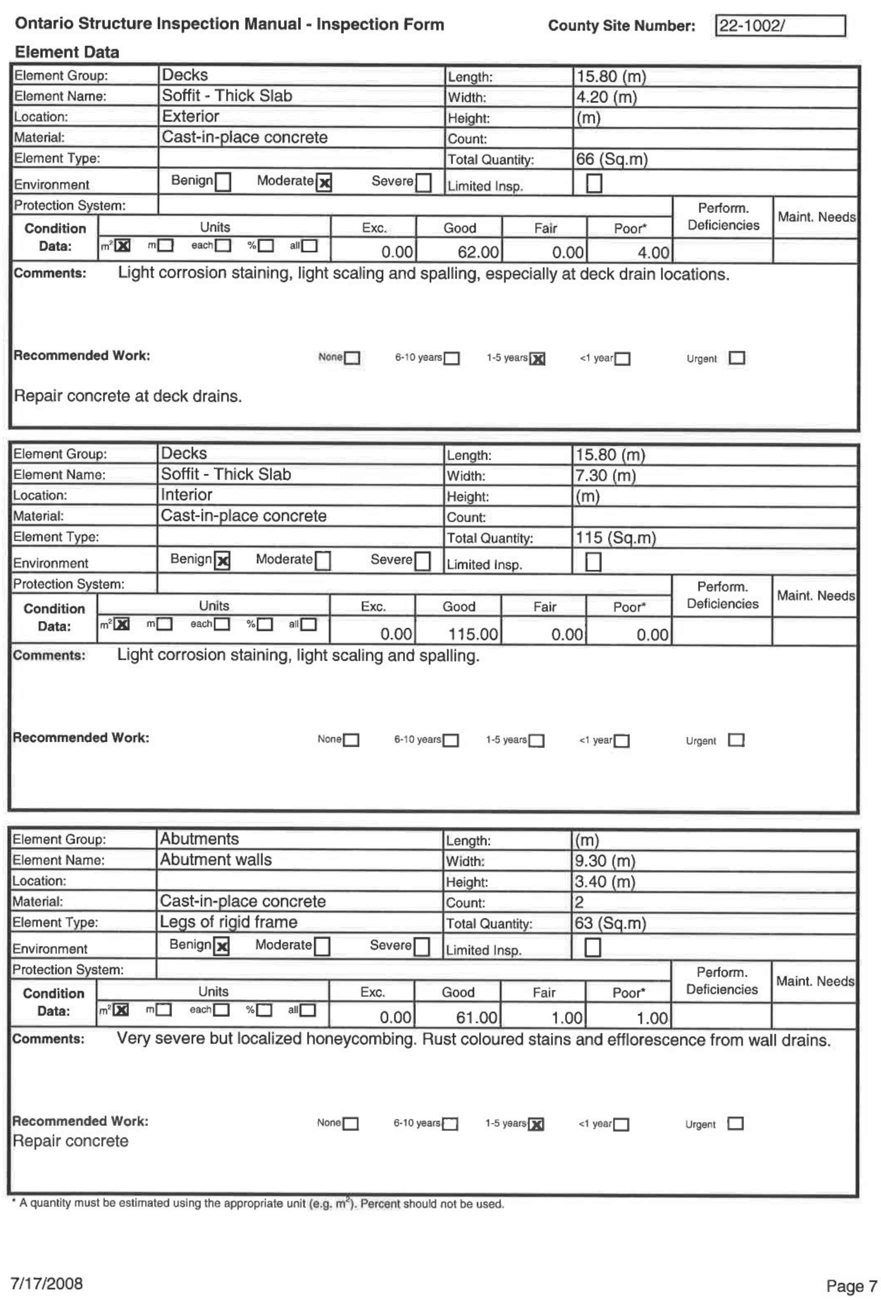
CHAPTER 1 INTRODUCTION

1.1 OVERVIEW

Large number of bridges in North America experience extensive deterioration due to aging, environmental impacts, excessive usage and other factors. In the United States, 24.94% of the national bridges are considered to be structurally deficient and functionally obsolete (NBI 2012). In Canada, around 8% of the Canadian bridges were completely rebuilt in the past 7 years and around 15% of them are more than 50 years old (Transport Canada 2012). Extensive effort has been made worldwide to develop and use Bridge Management Systems (BMS) in order to rationally and cost effectively managing bridge infrastructures. Bridge inspection and condition assessment are essential steps in BMS. They are utilized to identify most appropriate maintenance and rehabilitation actions that ensure public safety and prevent catastrophic events. Currently, inspection for defects is performed by visual inspection or by using non-destructive techniques. For instance, visual inspection is used to determine boundaries of delaminated areas in concrete bridge decks. Hammer sounding and chain dragging are the commonly used techniques for such purpose as well (Ahlborn et al. 2010). These tests determine the delaminated areas by noting sound changes while striking the concrete slab of the deck with a hammer or while dragging a chain over it (FHWA 2012). Visual inspection is dependent on the experience of the bridge inspector and as a result it is a highly subjective process. As an alternative, Non-Destructive Testing (NDT) techniques are used to evaluate subsurface conditions of bridge elements in a systematic way through using advanced technologies. One of the main limitations of NDT techniques, used in current practice and visual inspection, are the cause of traffic disruption and lane closure. Therefore, considering other class of technologies that capture data without direct contact with the structure such as remote sensing technologies is expected to be an alternative or to minimize the limitations stated above (Vaghefi et al. 2012). In addition, inspection reports of current practice describe bridge condition state in text format supported at times by images to document observed isolated defects. Thus, they lack visualization of the whole picture, i.e., the whole bridge with localized defects. Hence, considering a methodology to enhance condition assessment visualization will help in building more effective inspection in understanding bridges condition.

1.2 PROBLEM STATEMENT

Limitations and drawbacks of current practices in bridge inspection and condition assessment reduce the effectiveness of bridge management and its rehabilitation programs. Advanced technologies such as remote sensing have the potential to eliminate limitations of traditional bridge inspection practices. Current practices in bridge inspection cause traffic disruption and lane closure. In addition, current practices rely on completing manual reports during inspection where bridge inspectors assign a linguistic expression for condition state of each bridge element. Inspection reports typically do not include enough details on the extent of defects and their locations. Hence, a model to minimize traffic disruption and lane closure, and can improve condition state presentation for better overall understanding of the condition is needed. Figure 1-1 shows a sample condition assessment report (OSIM 2008). The research problem statement can be defined as “Propose a model to augment the current practice in bridge condition assessment by 1) minimizing traffic disruption 2) improving the presentation of the condition state.”



Ontario Structure Inspection Manual - Inspection Form **County Site Number:** 22-1002/

Element Data

Element Group:	Decks	Length:	15.80 (m)
Element Name:	Soffit - Thick Slab	Width:	4.20 (m)
Location:	Exterior	Height:	(m)
Material:	Cast-in-place concrete	Count:	
Element Type:		Total Quantity:	66 (Sq.m)
Environment	Benign ☐ Moderate ☒ Severe ☐	Limited Insp.	☐
Protection System:			

Condition Data: Units	Exc.	Good	Fair	Poor*	Perform. Deficiencies	Maint. Needs
m² ☒ m ☐ each ☐ % ☐ all ☐	0.00	62.00	0.00	4.00		

Comments: Light corrosion staining, light scaling and spalling, especially at deck drain locations.

Recommended Work: None ☐ 6-10 years ☐ 1-5 years ☒ <1 year ☐ Urgent ☐

Repair concrete at deck drains.

Element Group:	Decks	Length:	15.80 (m)
Element Name:	Soffit - Thick Slab	Width:	7.30 (m)
Location:	Interior	Height:	(m)
Material:	Cast-in-place concrete	Count:	
Element Type:		Total Quantity:	115 (Sq.m)
Environment	Benign ☒ Moderate ☐ Severe ☐	Limited Insp.	☐
Protection System:			

Condition Data: Units	Exc.	Good	Fair	Poor*	Perform. Deficiencies	Maint. Needs
m² ☒ m ☐ each ☐ % ☐ all ☐	0.00	115.00	0.00	0.00		

Comments: Light corrosion staining, light scaling and spalling.

Recommended Work: None ☐ 6-10 years ☐ 1-5 years ☐ <1 year ☐ Urgent ☐

Element Group:	Abutments	Length:	(m)
Element Name:	Abutment walls	Width:	9.30 (m)
Location:		Height:	3.40 (m)
Material:	Cast-in-place concrete	Count:	2
Element Type:	Legs of rigid frame	Total Quantity:	63 (Sq.m)
Environment	Benign ☒ Moderate ☐ Severe ☐	Limited Insp.	☐
Protection System:			

Condition Data: Units	Exc.	Good	Fair	Poor*	Perform. Deficiencies	Maint. Needs
m² ☒ m ☐ each ☐ % ☐ all ☐	0.00	61.00	1.00	1.00		

Comments: Very severe but localized honeycombing. Rust coloured stains and efflorescence from wall drains.

Recommended Work: None ☐ 6-10 years ☐ 1-5 years ☒ <1 year ☐ Urgent ☐

Repair concrete

* A quantity must be estimated using the appropriate unit (e.g. m²). Percent should not be used.

7/17/2008 Page 7

Figure 1-1 Sample of inspection report in Tecumseh, Ontario (OSIM 2008)

1.3 OBJECTIVES

Objectives of this research are to study different types of remote sensing technologies, to propose a systematic method for selecting most suitable technologies to be utilized based on specific parameters, and to propose a hybrid system of remote sensing technologies for bridge condition assessment. The system should be capable of detecting bridge defects, and be capable to enable visualization of inspection results in software that enhances presentation and understanding of collected inspection data. To achieve the above mentioned objectives, the following sub-objectives were determined:

1. Develop multi attributed decision support model to perform comparative evaluation for selecting remote sensing technologies based on decision maker preferences and project objectives.
2. Develop a hybrid inspection system using integrated remote sensing technologies to enhance current practices in bridge inspection.
3. Enhance visualization, presentation, and analysis of captured inspection data by employed remote sensing technologies.

1.4 METHODOLOGY

In order to achieve the objectives stated earlier, the following methodology was defined:

1. Conduct a comprehensive literature review to study current practice in bridge inspection, applications and limitations of current inspection processes.

2. Study the field of remote sensing technologies and evaluate their applications, and their potential use in bridge inspection.
3. Develop evaluation and ranking model utilizing flexible multi-attribute set of criteria; capable of generating recommendations for the best technologies to be implemented based on end-user preferences and project conditions.
4. Develop hybrid system of remote sensing technologies that can eliminate limitations of current practices.
5. Introduce suitable platform for data presentation and analysis that provides visualization capabilities for the generated inspection results of bridge condition assessment.
6. Validate the developed system by applying it to a case study of an actual bridge to verify its application and illustrate its usefulness.

Figure 1-2 shows a flow chart that depicts the different tasks and subtasks conducted to yield the proposed research results.

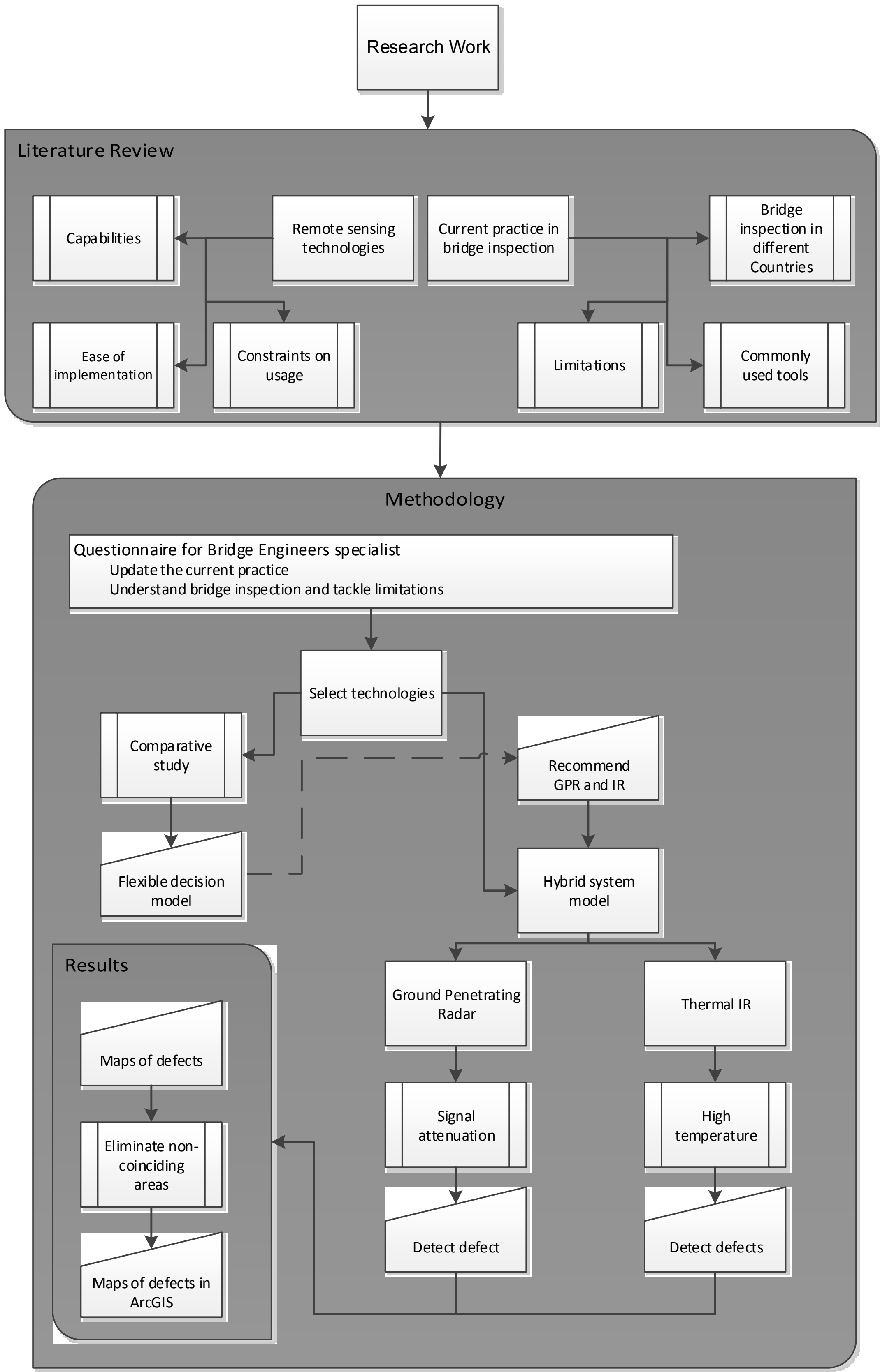


Figure 1-2 Thesis flow chart

1.5 THESIS ORGANIZATION

Chapter Two presents the literature review conducted on current practice and technologies used in bridge condition assessment. The first section of this chapter reviews the current bridge inspection practices worldwide and presents the findings in a summary. It focuses on the commonalities among different countries in the bridge inspection task and the current limitations. The second section of the chapter presents the results of a questionnaire survey conducted to reinforce the information obtained from the literature review and get solid information regarding the current practice from bridge professionals. The third section reviews remote sensing technologies, likely to be implemented in bridge inspection to overcome drawbacks of current practice mentioned in Chapters 1 and 2. The fourth section discusses the idea of integrated systems of technologies for individual technologies data interpretation improvements and for condition assessment enhancement. The fifth section overviews Geographic Information System (GIS) and summarizes ArcGIS applications in infrastructure management and bridge inspection; particularly in improving visualization of captured inspection data.

Chapter Three describes the first step in the developed methodology. It presents a comparative study of remote sensing technologies for concrete bridge condition assessment. The main concept in this chapter is to develop a model that proposes the most suitable remote sensing technologies to be utilized based on project objectives and end-user preferences. This model is flexible and the decision varies by the variation of each project as the decision is based on a flexible set of multi-attributed criteria. The overall achieved objective is the systematic approach in selecting technologies.

Chapter Four is the second step in the methodology. It suggests the utilization of two remote sensing technologies for bridge inspection. The use of the two technologies forms a hybrid system in the sense that the results of each technology will aid in delivering a better interpretation of the results of the other technology. The selection of the two technologies is based on the resources available for this research. The chapter proposes a framework for the model and for enhancing the output interpretation of each technology. In addition, it suggests a platform for data representation and reporting. The overall objectives are enhancing the accuracy of each individual technology and enhancing the visualization of the results obtained and the current condition. Then, the proposed system was implemented in a case study in the city of Laval, Montreal, Quebec, Canada. The case study was conducted on a section of a bridge. The bridge was also inspected using one of the current practice techniques, the hammer sounding test. The results were visually and numerically verified and they show a good correlation.

In Chapter Five, conclusions of the results and findings of this research are summarized, the limitations of the proposed system are stated, the main contributions to the current practice are presented, and the recommendations for future research in this area are listed.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter explains the findings of a detailed study to review current practices in bridge condition assessment and discusses the available literature on integrating remote sensing technologies in infrastructure management. Five main topics are presented. The first topic reviews the current bridge inspection practices in different countries around the world including Canada, the US, and selected European countries. The second topic presents the findings of a questionnaire conducted to review the current practice in bridge condition assessment. The third topic reviews remote sensing concepts and available technologies. Seven remote sensing technologies are reviewed and discussed. The fourth is mainly a review of the literature on integrated systems of remote sensing technologies in different applications. The last topic discusses ArcGIS and its applications in infrastructure management and bridge inspection.

2.2 CURRENT PRACTICE

2.2.1 Summary of the Current Practice

Bridge inspection practices have several commonalities among different countries worldwide. Visual Inspection is the main procedure in bridge inspection and is conducted on pre-specified periods of time. Bridge condition rating is assigned based on data obtained from inspection reports. Inspection may vary from one country to another on specific aspects such as intervals between consecutive inspections, types of inspections, and condition rating scales. Tables

2-1 and 2-2 summarize different bridge inspection manuals from several countries, inspection types used for concrete bridge decks, and the intervals between inspections. Table 2-3 summarizes the different rating scales used in different countries. (FHWA 2012; ABMIS 2008; TRB 2007; Queensland Department of Main Road 2004; OSIM 2000; Bevc et al. 1999).

Table 2-1 Inspection types and intervals in Canada

Province	Inspection Type	Description	Interval
Alberta	Level 1	Visual inspection and basic equipment.	Bridges on primary highways 21 months
	Level 2	In-depth inspection and the use of NDT.	Bridges on secondary highways 39 months
Ontario	Detailed visual inspection	Bridges with spans over 3m.	24 months
	Specialized Investigations	Uses NDT based upon the condition of the structure or when required by the detailed visual inspection.	<24 months
Quebec	Routine	Review previous inspection reports and perform visual inspection.	24-60 months
	Fracture-critical	Hands-on visual inspection and NDT.	As needed

Table 2-2 Inspection types and intervals in deferent countries

Country	Inspection Type	Description	Interval
USA	Routine	Visual inspection to identify bridges' condition.	24 months Max. 48 months
	Hands-on	Visual inspection and NDT.	72 months maximum
	In-depth	NDT may be used for in-	Based on criteria by

Country	Inspection Type	Description	Interval
		depth inspection.	NBIS
United Kingdom	General	Visual inspection of all components.	3 years
	Principal	Arms-length, visual inspection.	6 years
	Special	NDT as needed.	As necessary
France	IQOA	Visual examination.	3 years
	Detailed	Thorough visual inspection.	3-9 years
Austria	Superficial	Carried out by maintenance personnel during regular control drives.	-
	General	Carried out by bridge inspector under engineering supervision for accessible parts only.	2 years
	Major	Major inspection to all the parts of the bridge by simple or special devices.	6 years
Germany	Major test	Opening access doors, using lift equipment, and performing underwater inspection.	6 years
	Minor test	Using findings of major tests, level of effort may be increased if necessary.	3 years after major tests
Sweden	General	Visual inspection of components.	3 years
	Major	Arms- length, visual inspection and underwater inspection.	6 years
Denmark	Routine	Viewing the structure from top and bottom.	Annually
	Principal	Systematic visual inspection.	Every 6 years
Finland	Annual	Inspection by a foreman, no visual inspection or NDT performed.	Annually
	General	Visual inspection is performed and NDT is used if	4-8 years

Country	Inspection Type	Description	Interval
		necessary.	
Norway	General	Simple visual check.	1-2 years
	Major	Close up visual check for the entire bridge. May be supplemented by detailed investigation if required.	5-10 years
Slovenia	Superficial	Carried out by maintenance personnel during regular control drives.	-
	General	Carried out by bridge inspector under engineering supervision for accessible parts only.	2 years
	Major	Major inspection to all the parts of the bridge by visual inspection with the use of special devices.	6 years
Australia	Level 1	Might be carried out in conjunction with routine maintenance. Data will be recorded in inspection reports, and any major defects will be photographed.	Generally one inspection per year
	Level 2	Visual inspection of bridge components. Delivering a general condition rating for the whole structure.	Depends on the condition rating. Every year for condition 4 and from 2-5 years for conditions 1-3.
	Level 3	Detailed inspection for all the components to supplement visual inspection.	If recommended at level inspection or if a load capacity assessment id required.

*Inspection when a hazard happens is performed immediately, and usually any simple/general/routine inspection is dropped when a major/principle/in-depth inspection is being done.

Table 2-3 Condition rating in different countries

Country	Rating scale
Canada	Based on OSIM, elements are given a qualitative condition that ranges from excellent, good, fair, to poor condition. Alberta follows a scale form 9 (very good) to 1 (immediate action). Quebec uses the element condition report same as Ontario.
USA	Elements of each component is assigned a descriptive condition rate of “good”, “fair”, or “poor”. Each Component (mainly deck, superstructure, and substructure) are assigned a code condition rate, ranges from 9 (being excellent) to 0 (being failed), that follows the FHWA Coding Guide.
United Kingdom	Condition rating has two scales. A severity scale from 1 (no significant defect) to 5 (severe defects), and extension scale from A (no significant defect) to E (extensive defects)
France	Condition of the bridge is assigned after the IQOA inspection. Condition ratings are from 1 (good) to 3 (damaged). Ratings 2 and 3 are subdivided for urgent maintenance. A special condition “S” is used to reflect defects that may affect the safety of road users.
Austria	Condition rating is assigned to 12 different bridge elements. Ratings are assigned form 0 (no damage) to 5 (very heavy damage).
Germany	Condition rating ranges from 0 (good) to 4 (very poor). The bridge is assigned 3 different ratings one for each of the structural damage, traffic safety, and bridge durability. Then they are combined in the bridge management system to give final bridge component rating.
Sweden	Condition data are collect during general, major, and special inspection. Condition rate is given a number from 0 to 3, where 3 is the worst condition.
Denmark	The bridge inspector assigns the condition after the principal inspection every 6 years. The condition is assigned to 13 different components with scale from 0 (being excellent with no defects) to 5 (denoting a deteriorated bridge).
Finland	The bridge inspector assigns the condition after the general inspection every 5 years. The condition rate is assigned a number from 0 (being new or like new) to 4 (denoting a poor condition).
Norway	Norway has a condition rating using a scale from 1 (good) to 4 for four aspects: strength, traffic safety, maintenance costs, and aesthetics.

Country	Rating scale
Slovenia	Bridge is divided into 11 elements. The rating scales from 1 (critical) to 5 (very good).
Australia	Ratings are assigned to each structural component in order to obtain the structural condition rate that has a range from 1 (good) to 5 (unsafe).

ABIMS: Alberta Bridge Inspection & Maintenance System (ABMIS 2008)
TRB: Bridge Inspection Practices (TRB 2007)
OSIM: Ontario Structure Inspection Manual (OSIM 2000)
FHWA: Federal Highway Administration (Federal Highway Administration FHWA 2012)
NBIS: National Bridge Inspections Standards regulation (FHWA 2004)

Based on the above summary of the bridge inspection practices in Canada and around the world, the main commonality is the inspection procedures and the main differences are in the intervals and condition rating scales. The main inspection procedure is the visual inspection. NDT is being used when recommended, a detailed description of visual inspection and NDT will be mentioned in Sections 2.2.3 and 2.2.4. Inspection in North America is performed once every 2 years, and generally once every 3-5 years in Europe. Rating scales in North America use descriptive letter scales, and the US adopts a numerical rating scale on top of that. In Europe, they use numerical rating scales, and the UK adds another descriptive letter scale.

2.2.2 Discussions of Current Practice

Based on reviewing current practices in bridge inspection manuals as summarized in Tables 2-1, 2-2, and 2-3 the main observations are as follows:

- Bridge visual inspection is usually performed every 2 years on accessible parts of the bridge.

- A full detailed bridge inspection is performed every 5-10 years depending on regulations.
- Visual inspection is the main procedure in bridge inspection.
- Non-destructive testing techniques are used upon the recommendation of the bridge inspector only for specific elements of the bridge.
- Condition rating is assigned based on inspector's judgment and experience.
- Condition rating is usually assigned in the inspection that occurs every 2 years in North America and every 3-5 years in Europe.
- Overall condition rating is given as a qualitative measurement Table 2-4. In the U.S., a coding scale is also being used according to the FHWA Coding Guide (FHWA 2012).

Figure 2-1 is an example of Element Condition section adopted from an inspection form completed on a municipal bridge in Tecumseh, Ontario. The inspection process to complete the form followed the OSIM inspection procedure.

Element Data

Element Group:	Decks	Length:	15.80 (m)
Element Name:	Soffit - Thick Slab	Width:	4.20 (m)
Location:	Exterior	Height:	(m)
Material:	Cast-in-place concrete	Count:	
Element Type:		Total Quantity:	66 (Sq.m)
Environment	Benign ☐ Moderate ☒ Severe ☐	Limited Insp.	☐
Protection System:			

Condition Data:	Units	Exc.	Good	Fair	Poor*	Perform. Deficiencies	Maint. Needs
	m² ☒ m ☐ each ☐ % ☐ all ☐	0.00	62.00	0.00	4.00		

Comments: Light corrosion staining, light scaling and spalling, especially at deck drain locations.

Recommended Work: None ☐ 6-10 years ☐ 1-5 years ☒ <1 year ☐ Urgent ☐

Repair concrete at deck drains.

Figure 2-1 Element condition data

Table 2-4 Descriptive condition rating

Condition rate				
Interpretation	Excellent	Good	Fair	Poor
	No observed defect	Light/minor defect is observed	Medium defect is observed	Severe defect is observed

Table 2-5 Numerical condition rating

Code	Description
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 presented.
2	Critical Condition - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be presented 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 is presented in critical structural components, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put bridge back in light service.
0	Failed Condition - out of service; beyond corrective action.

2.2.3 Visual Inspection

Visual inspection is the main procedure for concrete bridge inspection. According to OSIM 2000, visual inspection is "*an element-by-element "close-up" visual assessment of material defects, performance deficiencies and maintenance needs of a structure... In many cases, the inspection should be conducted within arm's length of the element, possibly involving tapping with a hammer or making measurements by hand*". Visual inspection might take around 2 to 3 hours in a typical bridge (OSIM 2000) and might extend to a one half-day work (TRB 2007).

Typically, inspection is carried out once every 24 months. To conduct inspections, bridge inspectors are equipped with specific equipment, such as camera, chalk, marker, flashlight, and measuring tape and have special supporting equipment such as bridgemaster, bucket truck, and ladders. Inspectors need to review previous records of the structure to be inspected. Visual inspection is usually completed using simple-equipment tests such as hammer sounding and chain dragging for detecting surface defects (Ahlborn et al. 2010).

Surface concrete deck deficiencies such as cracks, wear, and spalls are visually inspected. Hammer sounding and chain dragging are used to determine the area at which the concrete is delaminated. A trained inspector will use a hammer to tap the concrete surface and notice the sound produced, where a "solid pinging" sound refers to sound concrete. Figure 2-2 shows the hammer sounding test. Chain dragging apparatus is composed of series of attached chains, the inspector will drag a chain over the concrete surface as shown Figure 2-3, and watch for sound changing. In this test a clear ringing sound refers to a sound deck and a muted and hollow sound refers to a delaminated deck (Gucunski et al. 2013).

Chain dragging is generally used to inspect the top surface of concrete decks rather than hammer sounding since hammer test is sometimes a slower process. Hammer sounding is used to inspect the bottom surface of concrete decks to define boundaries of delaminated areas where chains cannot be used (FHWA 2012). During inspection, the inspector assesses the overall adequacy of the bridge and identifies locations where more detailed inspection is required. The inspector also observes the bridge under truck load and notes any deflection or abnormality. The inspector usually fill out a report and records observations, writes down comments about the condition of the bridge, and takes photos while assessing the bridge condition. The report summarizes the findings of the inspector about deteriorated areas, defects locations, and a condition rating of elements inspected. Inspection findings are typically based on the inspector's judgment and experience.

Upon completing inspection, the inspector recommends a period for the next inspection that is normally two years or any time sooner if deemed to be necessary. Additional investigations may be suggested if the inspector felt a need. Severe material defects and deficiencies in performance are considered criteria for recommending additional investigations. Bridge inspector also specifies when the investigation should take place. Results obtained from previously mentioned techniques are subjective and rely on the inspector's experience due to lack of generic frameworks to generate quantitative results for bridge conditions. One of the attempts to overcome these drawbacks is the use of Non-Destructive Testing or Techniques (NDT) which also called Non-Destructive Evaluation (NDE) techniques in bridge condition assessment (Vaghefi et al. 2012).

Figure 2-2 Hammer sounding test (Gucunski et al. 2013)

Figure 2-3 Chain dragging test (Gucunski et al. 2013)

2.2.4 Non-Destructive Testing

NDT in general is the evaluation or examination of an object or an element to investigate the conditions which may affect the serviceability of the tested object without the need to change or alter its shape (Hellier 2001). It can be seen from Tables 2-1 and 2-2 that NDT techniques are currently used in several countries as a supplemental procedure for visual inspection if needed or when performing in-depth inspection. Some examples of popular NDT techniques are half-cell potential, impact-echo testing, and Ultrasonic Pulse Echo (FHWA 2012, Gucunski et al. 2013).

Half-Cell Potential test is used to locate active corrosion in the steel reinforcements embedded in concrete. The main procedure in this technique is measuring the electrical potential difference between the steel reinforcements and a standard portable reference electrode placed on the surface of the concrete. A pre-defined grid is designed to assign locations where potential differences are measured. The electrode is connected to the negative end of the voltmeter and the other end on concrete is connected to the positive side. The measured values will be plotted on a diagram of the inspected structure as a contour map. ASTM C876-91 1999 summarizes the procedure to interpret half-cell potential results. Basically, if the potential is greater than -200 mV then the probability of corrosion is less than 10%, while if the potential is lower than -350 mV then the probability of corrosion is greater than 90%. All the values between these two limits are drawn in the contour map (Rhazi 2009).

Impact-Echo Testing is one of the reliable NDT techniques conducted to detect concrete delamination and identifying dimensions in concrete decks (Lin and Sansalone 1996). The main procedure performed in this method is detecting and characterizing wave resonators in a concrete bridge deck. This can be done by striking the inspected object, by a wire-mounted steel ball for example, and measuring the response at a close location using a sensor. The reflected frequency, called the return frequency, will be used to measure the depth of the reflector. The depth of the reflector determines the state of the concrete. Shallow reflectors represent delamination and deep reflectors represent sound concrete. That is because the sharper the contrast in acoustic impedances of materials the stronger the reflector will be. For instance, in sound concrete the dominant reflector is the bottom of the concrete in which the air-concrete interface has a contrast in acoustic impedance (Gucunski et. al 2013).

Ultrasonic Pulse Echo is a method mainly used to detect objects, interfaces, and anomalies such as cracks, voids, and delamination. This can be achieved by transmitting high amplitude pulses through the inspected object. The basic principle applied is measuring the time or velocity of the ultrasonic waves being transmitted through the object and reflected back to the surface. Defects are identified where difference in impedance occurs. Therefore, deteriorated regions in the concrete will appear as areas with lower velocity waves compared to sound concrete (Gucunski et. al 2013). More information regarding other NDT techniques is presented in Gucunski et al. 2013.

2.2.5 Concrete Defects

Concrete defects are the main challenges addressed in inspection. Defects may develop either on surface or in subsurface of concrete. Some types of defects can be superficial without causing a need for maintenance such as scaling. Other types of defects may cause serious damages to the concrete as they progress. Corrosion of steel reinforcements causes a significant increase in steel bars' volume, which results in causing stresses on surrounding concrete leading to internal cracks. When corrosion propagates in steel and evolves to severe corrosion, internal cracks will progress to cause loss of bond yielding delamination. Serious damages to concrete will occur when a series of delaminated areas form into spalls that deteriorate to the surface causing structural disintegration (Moufti 2013). Descriptions of several types of concrete defects are mentioned in Table 2-6 (Ahlborn et al. 2010, OSIM 2000).

Table 2-6 Concrete Defects

Defect	Description
Scaling	Local loss of surface portion due to freeze-thaw cycles. Causes of scaling might be due to poorly finished concrete or overworked concrete where not enough entrained air is found at the surface.
Disintegration	Physical breaking of concrete into smaller pieces. Causes are due to progression of scaling to develop disintegration or due de-icing chemicals, chlorides, or by frost.
Erosion	Deterioration brought by water-borne sand and gravel against the surface. Caused by flowing ice. It is combined by the chemical reaction between air and water-borne.
Corrosion of reinforcement	Deterioration of reinforcement by electrolysis coming from chloride ions dissolved in water. At first stages it appears as rust stain. At severe stages, surface concrete above

	reinforcements cracks, delaminate, and spalls.
Delamination	Discontinuity of surface concrete that subsequently separates but not entirely detached. It starts with corrosion of reinforcements and the resulted cracking in concrete.
Spalling	Concrete completely detached from larger areas. It is the continuation of delamination along with excessive external loading and internal cracking.
Cracking	Linear fracture in concrete that partially of entirely extends through concrete. It is caused by tensile stresses in concrete that exceeds the tensile capacity of concrete.
Expansion joints	Problems associated with torn, armored plate damage, chemical leaching, or cracks within two feet from the joint.
Changes in length and settlement	Change in length is a horizontal change due pavement shove. Settlement is the vertical movement of the bridge. Both cause cracks in concrete. Settlement might cause severe damage within the structure.

2.2.6 Limitations of Current Practice

Several drawbacks of the current practice have been summarized from OSIM 2000, TRB 2007, Washer et al. 2010, FHWA 2012, and Vaghefi et al. 2012. Below is the summary of the limitations.

- In Canada based on OSIM 2000 the condition data is divided into four qualitative condition states (Excellent, good, fair, and poor) and the condition assignment is based on inspector judgment. The inspector divides the total quantity inspected into segments and then assigns each segment a level of condition based on his/her judgment. In the example in Figure 2-4, the inspector decided to give 60.5/65 m^2 a good state and 3.5/65 m^2 a poor state.
- Current inspection has limited accessibility to different bridge elements. If an element is not visible, quantities will be estimated yielding to inaccurate

condition assessment. According to OSIM 2000 "*If an element is not completely visible, or the view is obstructed, quantities should be estimated and the "Limited Inspection" box should be checked on the form*."

- Limited visualization of bridge condition and interrelation among different defects locations. Defects are described by words. Comments are used to provide general information about the element state. In Figure 2-4 comments has been used to explain locations and levels of severity of defects in the wearing surface (OSIM 2008).
- Recommendation of next task is limited to whether or not performing rehabilitation and it is suggested by inspector too. Recommendation doesn't include maintenance or additional investigation (OSIM 2000).

Element Group:	Approaches	Length:	3.80 (m)
Element Name:	Wearing surface	Width:	8.40 (m)
Location:		Height:	(m)
Material:	Asphalt	Count:	2
Element Type:		Total Quantity:	64 (Sq.m)
Environment	Benign ☐ Moderate ☐ Severe ☒	Limited Insp.	☐
Protection System:			

Condition Data:	Units	Exc.	Good	Fair	Poor*	Perform. Deficiencies	Maint. Needs
	m² ☒ m ☐ each ☐ % ☐ all ☐	0.00	60.50	0.00	3.50		

Comments: Severe alligatoring at road edges and light settlement at end of approaches

Recommended Work: None ☐ 6-10 years ☐ 1-5 years ☐ <1 year ☐ Urgent ☐

* A quantity must be estimated using the appropriate unit (e.g. m²). Percent should not be used.

Figure 2-4 Element condition data (OSIM 2008)

- Photos are used to illustrate on the defects and the surrounding sound areas. They are not included in the analysis process.

- Lane closure is almost occurring at every detailed visual inspection event (FHWA 2012, TRB 2007)
- Delamination cannot be detected using visual inspection until it has progressed to reach spalling or advanced deterioration; because deterioration usually develops at the level of rebars because of the expansion and stresses caused by corrosion (Washer et al. 2010).
- The main mutual limitation of the NDT is the cause of traffic disruption and lane closure (Vaghefi et al. 2012).

2.3 Questionnaire

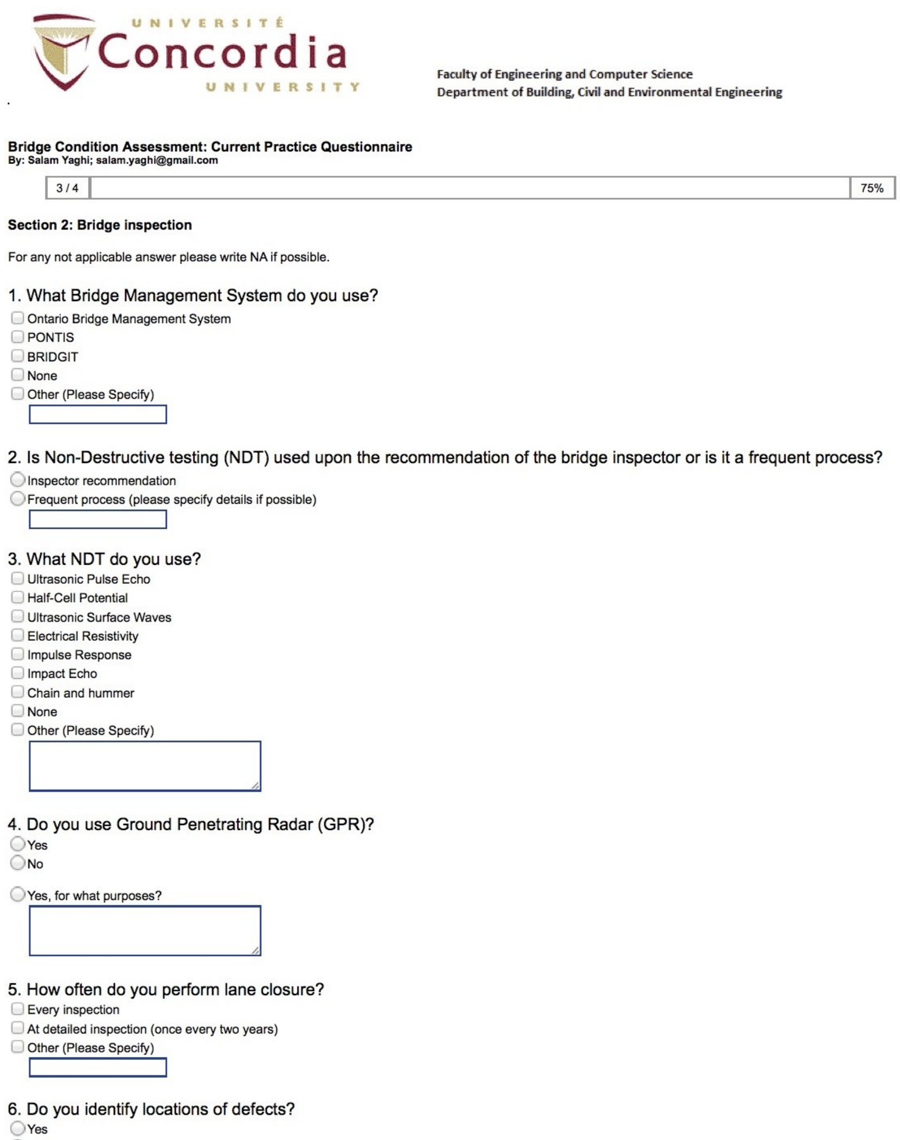
A questionnaire was sent to professionals in the field of bridge inspection and condition assessment. The main objectives of the questionnaire can be summarized as:

- Update the current practice of bridge inspection.
- Reinforce the information gathered in Section 2.2.
- Obtain statistical information regarding bridge inventory
- Study the usefulness of NDT in bridge condition assessment

2.3.1 Part 1

The questionnaire was distributed among bridge professionals who range from senior engineers and project managers to project engineers and civil engineers. It was sent directly to 53 participants. The response rate was 40% with a questionnaires returned with full answers.

In Part 1 of the questionnaire, personal information were solicited including years of experience, firm name, position, and specialization. The average years of experience of the respondents is 18 years with 60% of them possess over 10 years of experience. Around 24% of the respondents were senior engineers and 19% were managers. Figure 2-6 shows pie charts distribution regarding the years of experience (left) and positions of respondents (right). Over 46% of the respondents were working in international firms.



UNIVERSITÉ Concordia UNIVERSITY

Faculty of Engineering and Computer Science
Department of Building, Civil and Environmental Engineering

Bridge Condition Assessment: Current Practice Questionnaire
By: Salam Yaghi; salam.yaghi@gmail.com

3 / 4 75%

Section 2: Bridge inspection

For any not applicable answer please write NA if possible.

1. What Bridge Management System do you use?
- Ontario Bridge Management System
- PONTIS
- BRIDGIT
- None
- Other (Please Specify)

2. Is Non-Destructive testing (NDT) used upon the recommendation of the bridge inspector or is it a frequent process?
- Inspector recommendation
- Frequent process (please specify details if possible)

3. What NDT do you use?
- Ultrasonic Pulse Echo
- Half-Cell Potential
- Ultrasonic Surface Waves
- Electrical Resistivity
- Impulse Response
- Impact Echo
- Chain and hummer
- None
- Other (Please Specify)

4. Do you use Ground Penetrating Radar (GPR)?
- Yes
- No
- Yes, for what purposes?

5. How often do you perform lane closure?
- Every inspection
- At detailed inspection (once every two years)
- Other (Please Specify)

6. Do you identify locations of defects?
- Yes

Figure 2-5 Sample of online questionnaire

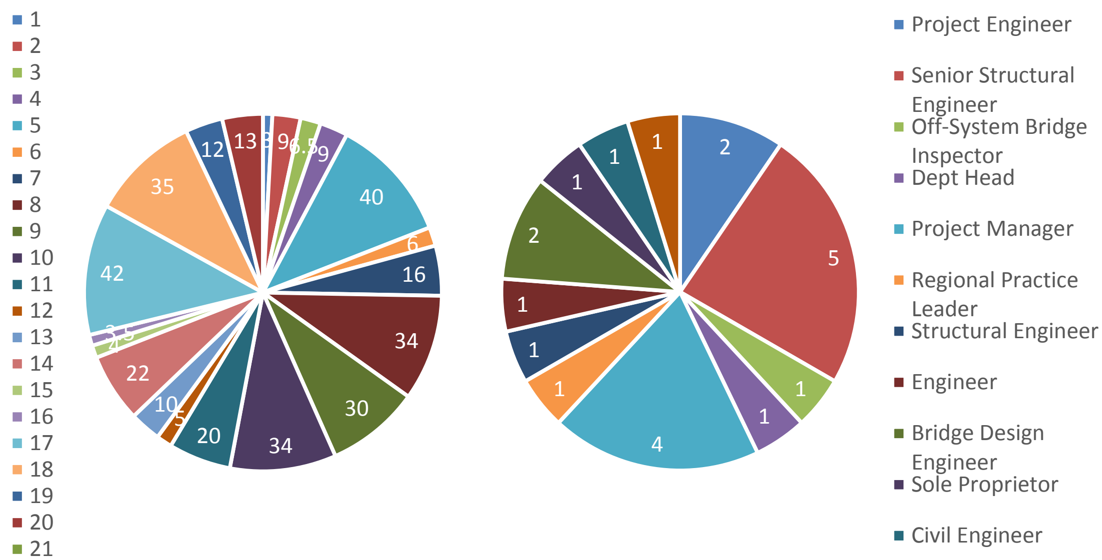


Figure 2-6 Left: Respondents years of experience – Right: Respondents positions

2.3.2 Part 2

Part 2 of the questionnaire was designed to solicit statistical information on the statues of bridges in inventory. Information regarding number of bridges in inventory, average age, and average rating of bridges are being surveyed. Below is a sample of the questions addressed with the percentage of responses received for each answer in every question. Table 2-7 shows answers received from every respondent regarding number of bridges, average age, and average rating. Number of bridges ranges from hundreds to thousands in each record. The average age of bridges is 59 years with around 42% being over 50 years old. The overall condition rating of bridges is satisfactory.

Question	% of Respondents	Number of Respondents
Do you keep a database for bridge inventory?		
Yes	16.00%	4
No	52.00%	13
Other	32.00%	8
Number of respondents		25
Breakdown of the bridges:		
Concrete Bridges	38.46%	10
Prestressed Concrete Bridges	23.08%	6
Steel Bridges	38.46%	10
Number of respondents		26
What is the average age of the bridges?		
Number of respondents	100.00%	12
What is the average rating of the bridges inventory?		
Number of respondents	100.00%	7

Table 2-7 Part 2 questions details

Bridges breakdown (number of bridges)			Average Age (years)	Average Rating
Concrete	**Pre-stressed**	**Steel**		
34%	3%	57%	40	5
6581	3274	2700	50	78
600	57	15	30	fair
30	100s	180	30	6
Data base	30	100s	45	we are not rating them
100s	15	0	40	
82		N/A	70	
1780		200	20	B
20		5	90	Good
2000		4000	45	
			100	
			150	
			Average: 59	**Satisfactory**

2.3.3 Part 3

Part 3 collects information regarding current practices in bridge inspection. One main objective was to investigate the use of NDT and GPR. Also, questions regarding collected data storage and analysis were included in the questionnaire. Sample of the questions is shown below. In general, 71% of the respondents stated that NDT techniques are being used when required by bridge inspectors. Around 21% of the respondents indicated that hammer sound and chain drag are the commonly used techniques. Around 74% of the respondents do not use GPR for inspection. Lane closure is performed during biennial inspection and in some other ad-hoc inspections. Microsoft Excel is the most commonly used software for data storage and analysis. About 47% of the respondents use Excel for data storage and 40% of the respondents use it for data analysis.

Question	% of Respondents	Number of Respondents
Is Non-Destructive testing (NDT) used upon the recommendation of the bridge inspector?		
Inspector recommendation	71.43%	15
Other	28.57%	6
	Number of respondents	21
What NDT do you use?		
Ultrasonic Pulse Echo	16.28%	7
Half-Cell Potential	16.28%	7
Ultrasonic Surface Waves	9.30%	4
Electrical Resistivity	4.65%	2
Impulse Response	6.98%	3
Impact Echo	6.98%	3
Chain and hummer	20.93%	9
None	2.33%	1
Other	16.28%	7
	Number of respondents	43
Do you use Ground Penetrating Radar (GPR)?		
Yes	5.26%	1
No	73.68%	14
Other	21.05%	4
	Number of respondents	19
How often do you perform lane closure?		
Every inspection	14.29%	3
At detailed inspection (once every two years)	38.10%	8
Other	47.62%	10
	Number of respondents	21
Do you identify locations of defects?		
Yes	100.00%	20
No	0.00%	0
	Number of respondents	20
If yes, do you keep record of the defects details?		
Yes	94.74%	18
No	5.26%	1
	Number of respondents	19
What is the computational platform of data storage and data analysis? (example: MS excel, MATLAB,…, none)		
Data Storage		15
Data Analysis		10
	Number of respondents	25

2.3.4 Conclusions

Conclusions were made after collecting and analyzing the questionnaire responses. The conclusions serve in understanding the current practice from a professional perspective, and they reinforce the information summarized in Section 2.2 form a theoretical perspective. In addition, the questionnaire helped in defining objectives for the methodology to overcome some of the problems addressed in the questionnaire. Below is a summary of the conclusions drawn from the questionnaire.

- Transportation infrastructure includes a large bridge inventory ranging from hundreds to thousands of bridges in each inventory.
- The average bridges age based on the collected sample is 59 years.
- The average overall condition rating of bridges in the inventory of the questionnaire is satisfactory.

Those conclusions motivated current research to create a methodology that assesses bridges in the best manner. Consequently, maintenance and rehabilitations actions can be applied efficiently on the large number of bridges. Otherwise, the bridges are getting older with time and their condition will reach below satisfactory which might lead to catastrophic events, more conclusions as follows.

- Non-destructive techniques are being used by the recommendation of the bridge inspector.

- Several NDT techniques are not being utilized often and the reliance is on hammer sounding and chain dragging.
- Ground Penetrating Radar is not being implemented, and if so, it is for strands or rebars detection generally.
- Lane closure is being performed every detailed inspection (every two years) and also on other occasions.
- The main software used for data analysis and storage is Microsoft Excel.

Based on the second part of conclusions, several actions should take place. Improving inspection processes is required as NDT techniques, which are considered advanced techniques, are still not in operation due to several technical reasons. Microsoft Excel is the main software used with limited abilities and other advanced software can be considered such as ArcGIS with advancements in building maps and wireless databases access. Hence, considering an improved methodology for bridge inspection is required, such methodology should have several features: 1) Being similar to the current practice 2) Can overcome the main limitation of causing traffic disruption 3) Utilizes advanced techniques for bridge inspection.

Therefore, the proposed methodology discussed in Chapters 3 and 4 can be delivered to enhance current bridge inspection. The proposed methodology is utilizing state-of-the-art technologies in bridge inspection and professional software for data visualization. The use of technologies and the software is preliminary and not covering their full capabilities, but it serves the purpose of the research. The following Sections will discuss hi-tech technologies in the field of remote sensing technologies that have the ability of minimizing traffic disruption. Further, available literature on the use of professional software called ArcGIS for enhancing bridge condition assessment visualization is provided.

2.4 REMOTE SENSING TECHNOLOGIES

2.4.1 Introduction

Remote sensing is the process of collecting, measuring, and interpreting spatial information of an object from a distance without direct contact (Sabins 1986, Ahlborn et al. 2010). Remote sensing technologies are being used in different fields such as agriculture, geotechnical applications, mine detection, and oil and gas pipeline. The use of remote sensing technologies is relatively new in the field of bridge inspection. Nevertheless, these technologies are promising in terms of providing improvements to the traditional inspection processes (Ahlborn et al. 2010). Several remote sensing technologies can be applied in bridge condition assessment (Vaghefi et al. 2012). Seven of these technologies are selected for the current research, namely: Thermal Infrared (Thermal IR), Bridge Viewer Remote Camera System (BVRCS), Synthetic Aperture Radar (SAR), Light Detection and Ranging (LiDAR), 3D Optical Bridge Evaluation System (3DOBS), Digital Image Correlation (DIC), and Ground Penetrating Radar (GPR). Table 2-8 includes definitions of these technologies.

Table 2-8 Remote sensing technologies implementation

Technology	Definition
Thermal IR	Measuring the intensity of radiant that is being transmitted by an object by using a thermal infrared camera in order to detect defects.
BVRCS	Consists of two cameras attached to a vehicle that take photos of bridges for later analysis for defects.
SAR	SAR utilizes microwave signals transmitted from a sensor mounted in a satellite or an airplane to scan areas. The high frequency microwave has penetrating abilities, so it can be used to detect subsurface defects.
LiDAR	LiDAR is a technology that works on microwaves. It works on timely measured light pulses. It scans bridge surfaces to develop 3D models.
3DOBS	3DOBS works on the principal of photogrammetry. A Camera is attached to a vehicle, photos taken are 60% overlapped when combined to develop a 3D model for analysis.
DIC	DIC is the correlation or comparison between two optical (regular) images of the same object, with time difference, based on a pixel by pixel analysis.
GPR	GPR is a type of radar that utilizes low frequency waves and a wide bandwidth to maximize the penetration of the waves. It's mainly used to detect delamination in subsurface concrete. GPR can be air-coupled or ground-coupled.

2.4.2 Infrared Thermography (IR)

IR concept is based on capturing and analyzing thermal radiations of an object by recording thermal images. The thermal image is taken by an IR camera. This camera measures the intensity of radiant that are being transmitted by an object, and records variations of the surface temperature as an image. After that a process called thermography will be conducted in which the data obtained from the thermal image is being collected, analyzed, and interpreted.

Thermography works based on the principle of heat disruption inside the object being under study. The heat disruption is caused by defects and anomalies in the object subsurface and can be measured on the surface by using IR cameras. The anomalies and defects such as delamination can be seen as hot or cold spots in thermal images depending when images were taken.

IR thermography has a wide range of applications; it has the ability of identifying and detecting bridges surface defects such as cracks, delamination, spalling, scaling, and expansion joints. In addition, it can detect subsurface problems such delamination, spalling, and scaling. IR thermography cannot recognize corrosion in steel reinforcement however (Ahlborn et al. 2010; Washer et al. 2010). Figure 2-7 shows the ability of IR in detecting subsurface delamination (Washer et al. 2010).

IR can be used for bridge inspection. During daytime, temperature is typically high increasing the temperature of the surface of the deck, the parts of the surface that lies above delaminated areas in the subsurface will warm up faster and will appear as hot spots. During night, the opposite happens; the surface above delaminated areas will cool down faster and will appear as cold spots (Washer et al. 2010).

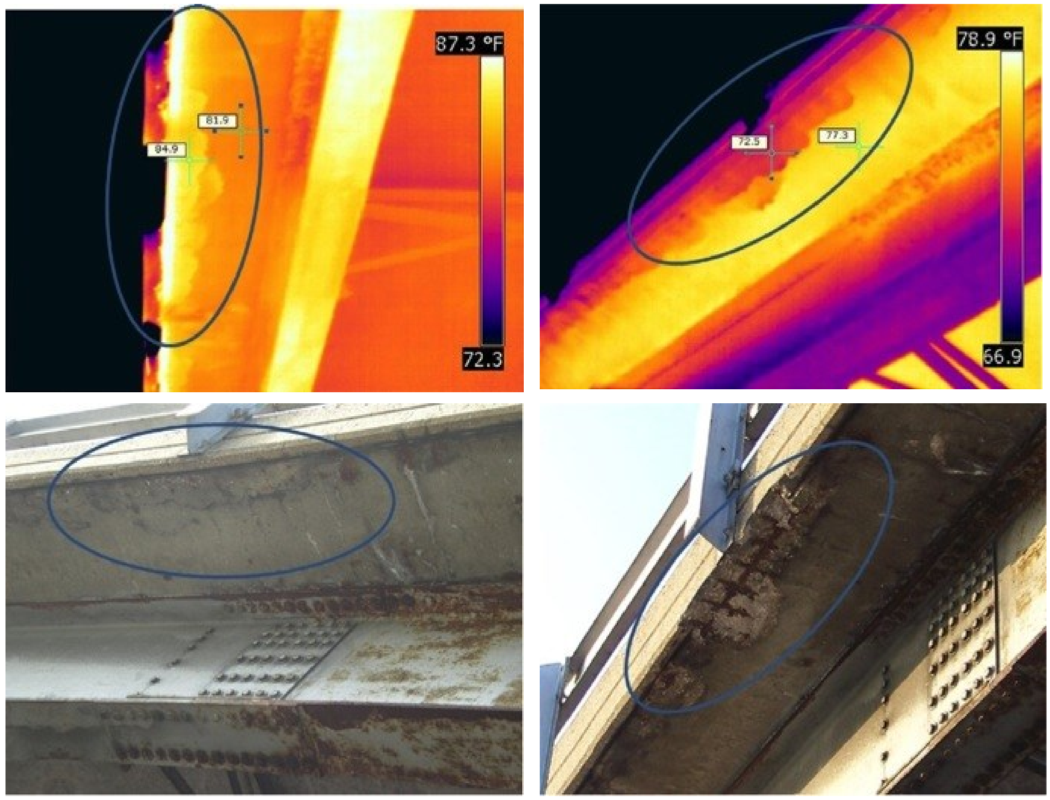


Figure 2-7 IR Detecting subsurface defects (Washer et al. 2010)

IR applications in bridge condition assessment have advantages and limitations. IR advantages include the ability of detecting subsurface defects, up to two inches under the surface, such as delamination and the ability of evaluating extent of surface defects as they are exposed to sunlight. In addition, this approach can reduce traffic disruption and lane closure caused by other technologies. Problems associated when utilizing IR is occurs when interpreting IR images, as they might be difficult if some areas on the surfaces are being heated and other areas are not due to weather conditions. Sensitivity to the temperature could be a limitation. IR cameras can differentiate up to 0.08 C^{o} this might add complexity to the image in the analysis process. It is important to take optical (regular) images of the concrete surface with each thermal image being taken; because dirt, moisture, and staining on the concrete surface would appear as hot spots on the concrete surface. Therefore it is important to compare thermal images with optical images to eliminate misleading understandings (Vaghefi et al. 2011, Bremner et al. 2001).

2.4.3 Bridge Viewer Remote Camera System (BVRCS)

The bridge viewer remote camera system (BVRCS) is a system consisting of two cameras that are attached to a vehicle in order to take photos of a bridge deck and other parts. This technology is considered to be a low cost system that can provide bridge specialists with a series of photos tagged to their different locations. The photos are usually being used as references while studying current condition or when studying changes occurring over time. This system can replace the current practice of field crews that capture photos of only major problem areas. In addition, by providing bridge engineers with a series of photos of the bridge that are tagged to their locations, they can easily review and assess the state of the bridge remotely and economically while being at the office.

Using this technology is simple, by driving over the bridge; the cameras will be used to take the photos required of the bridge deck. Comparing to the current practice, the bridge engineer will stay safer, as the photos are being taken from cameras mounted to vehicles, and minimal traffic disruption will be caused. This system can be used either to take HD videos or to take static photographs. Taking static photos is cheaper. BVRCS can cost less than $1000 to attach cameras to vehicles and take photos of bridges (Ahlborn et al. 2013).

Figure 2-8 depicts the utilization of BVRCS technology and the ability of studying surface of bridge deck (Vaghefi et al. 2012).

Figure 2-8 Part of a bridge taken with BVRCS (Vaghefi et al. 2012)

One advantage of utilizing BVRCS is when bridge inspectors study bridges they have already inspected in the past so they can check the bridge photo inventory before the following inspection session. BVRCS are most advantageous in assessing bridge deck surfaces such as, according to Ahlborn et al. 2010, studying “torn or missing expansion joint seals, damage to armored expansion joint plating, cracks and spalls near expansion joints, map cracking, scaling and spalling of the bridge deck, and delamination expressed as surface cracks”.

2.4.4 Synthetic Aperture Radar (SAR)

Synthetic Aperture Radar (SAR) is a unique remote sensing device that is distinguishable from other optical satellite photos or radar devices. It can provide spatial and temporal high resolution data with presence or lack of light and under any weather condition. This is due to the fact that SAR systems work under microwave signals instead of infrared or visible light waves that other technologies utilize.

Electromagnetic waves, such as microwaves, by nature are not affected by light concentration. In addition, SAR's high frequency electromagnetic waves, which range usually between 1 and 20 GHz, make this system unaffected by clouds and different weather conditions. The microwaves penetrate through clouds deep to the point of interest with minimal loss of information. This system acquires its information by sending electromagnetic waves using a transmitter to the target and then receiving the reflected waves back at the receiver. Depending on the target's geometry, orientation, and material properties, it will either reflect or absorb the electromagnetic waves sent from the SAR system. Target's geometry such as its shape and size will determine how waves will be reflected.

By analyzing how waves got reflected back to the receiver, the SAR system can recognize the geometry. Material properties such as permeability and permittivity determine how much waves are being absorbed by or reflected off the surfaces. Finally, what makes SAR systems more distinguishable than other radars is its ability to determine subsurface properties in addition to the surface properties (Shinozuka and Loh 2004).

SAR can be used to detect some surface and subsurface defects of bridge decks. Changes in bridge length, position, and settlement can be determined using SAR (Ahlborn et al. 2010). Al-Fares 2005 was studying the use of SAR to determine the surface deformation in karstic regions. Kharkovsky et al. 2011 are trying to utilize the use of SAR to determine subsurface anomalies such as detecting corrosion in steel reinforcement in bridge decks shown in Figure 2-9. The authors have experimented SAR technique on steel bars in different boxes at different depths, bar sizes, and spacing between bars. Their research is still preliminary and they had the ability of detecting bars with and without rust at different frequencies ranges from 8.2 GHz to 26.5 GHz. Their future work will focus on detecting changes in bars volume to estimate the severity of corrosion.

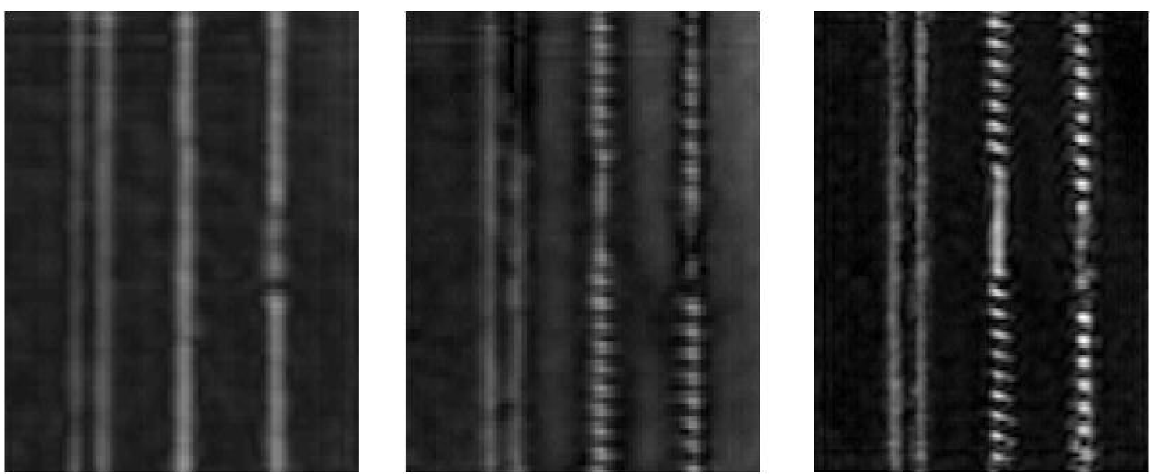


Figure 2-9 SAR detecting reinforcements at different frequencies (Kharkovsky et al. 2011)

2.4.5 Light Detection and Ranging (LiDAR)

Light Detection and Ranging (LiDAR), or sometimes called LaDAR (Laser Detection and Ranging), is a remote sensing technology that works on microwaves. LiDAR systems work on timely measured light pulses. It consists of a transmitter, a receiver, and a signal processing unit. The time that the light pulses take to go from the transmitter and reflect back off an object to the receiver is measured. By using the speed of light, distance between the LiDAR and the object will be calculated (Liu 2010). There are two ranges for LiDAR measurement, a time-of-flight and a phase shift technology. The time-of-flight is basically described earlier, as by calculating the distance using time and speed of light. Phase shift technology however, can calculate the distance by measuring phase shifts between the transmitted and received microwaves. Some advantages of using LiDAR is that it does not require any wire connected to the target, it does not depend on light, and it provides information about bridge members without the hazard of reaching them (Laefer et al. 2009).

LiDAR has a wide range of applications; it's mainly used for developing a 3D model of the bridge. This model is of great importance as it provides a precision up to 1 mm^2. Out of the 3D model, the LiDAR can be used to detect surface defects like mass loss, spalling, scaling, delamination, cracking, and expansion joints (Chen et al. 2011; Ahlborn et al. 2010; Laefer et al. 2009). Endsley et al. 2012 showed in their study that developing a 3D model utilizing a high resolution LiDAR system can generate useful information about bridge deck's surface problems such as locations of spalls and surface cracks as shown in Figure 2-10.

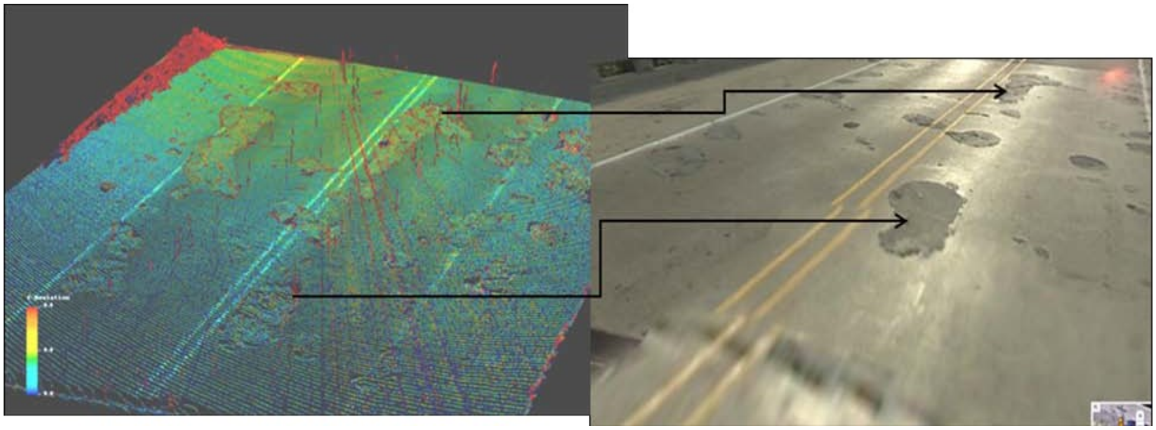


Figure 2-10 A model of a bridge deck using LiDAR (Endsley et al. 2012)

2.4.6 3D Optical Bridge Evaluation System (3DOBS)

3D Optical Bridge Evaluation System (3DOBS) works on the principle of photogrammetry. It is a technology that utilizes commercially available photogrammetric hardware to take photos of bridge decks. These cameras can be mounted on vehicles or be ground-based. Depth and height measurement can be interpreted from photos, yet they cannot be gotten from a single photo. Therefore, the basic principle in this system is that the data obtained are from two images taken from different angles of the same object and are at least 60% overlapped when combined. To achieve the required resolution, the images are better being captured at a much lower standoff distance (Vaghefi et al. 2012). The 3DOBS is considered to be a low cost system, an easy to implement, and an effective tool in detecting some of the bridge surface defects.

3DOBS is mostly used to develop 3D models of bridge decks in order to extract information like area of spall and delamination. Vaghefi et al. 2013 were able to develop a 3D model of a bridge deck utilizing two software, Agisoft PhotoScan which has the ability of generating 3D model from several photos.

The second software is ArcGIS which was used to calculate the volume of each individual of the spalled areas. Figure 2-11 shows the utilization of the system in detecting surface defects by taking several images and by overlapping all images by 60% (Ahlborn et al. 2013).

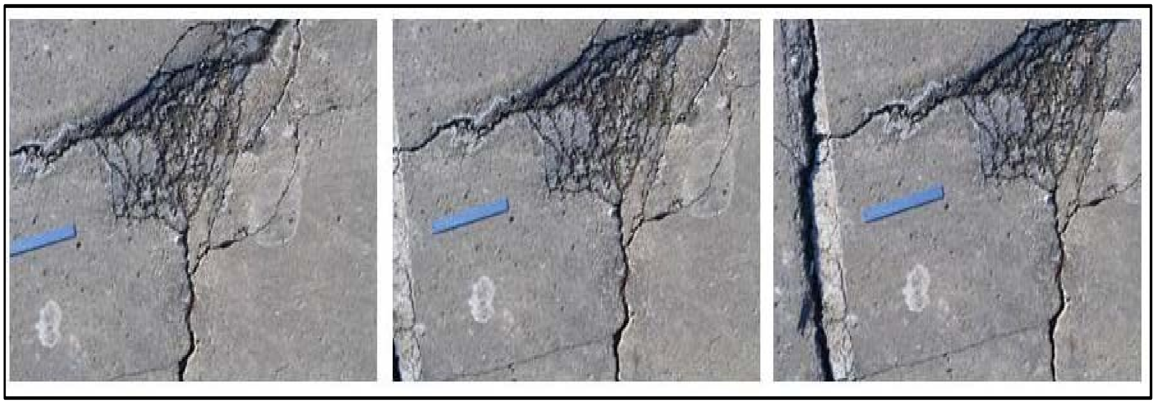


Figure 2-11 3DOBS application in calculating the surface defects (Ahlborn et al. 2013)

Ahlborn et al. 2013 reported that the total system cost was $4320 and it is a one-time payment. Therefore, it can be considered as a low-cost effective technology in detecting bridge spall area and volumes.

2.4.7 Digital Image Correlation (DIC)

DIC refers to Digital Image Correlation. As a definition, DIC is the correlation or comparison between two optical (regular) images of the same object, with time difference, based on a pixel by pixel analysis. The analysis will be done using computer algorithms and software. These algorithms have the ability of measuring displacement and movement of certain features of the object. Some of the algorithms that are being in use are a MathWorks open source DIC, DDIT on MATLAB, and Vic-2D software. DIC can obtain data with high spatial resolution of up to 2.5 mm when it is performed at a close stand-off distance.

However, to achieve this high resolution, a much close stand-off distance is required, which will in turn reduce the coverage area of each single photo. In other words, more pictures are required to cover the same area if higher resolution is to be maintained. One of the main drawbacks of this technology is that to perform an analysis on two pictures, the camera should then be placed at the same location to capture the same image. Thus, if the time difference between the two images is a year or more, this will complicate the process specially when considering environmental effects (Ahlborn et al. 2013; Ahlborn et al. 2010).

Based on that, the basic applications of DIC are all concentrated on the surface. It can be used to detect a change in bridge length, bridge settlement, transverse movement of the bridge, and measuring the vibration of a bridge or structural element (Ahlborn et al. 2010).

Figure 2-12 shows the use of DIC (Vaghefi et al. 2011). A pattern of pant dots was made on an I-beam section as shown in part A of the figure. Certain contrast was achieved in part B for the post processing step. Displacements on the beam section were enforced. The response diagram of the projected paint dots was plotted as shown in part C using an automated computer algorithm. The findings of the study showed the sufficiency of DIC application in measuring rigid displacement, local deformation, global displacement, and detecting a change in bridge length.

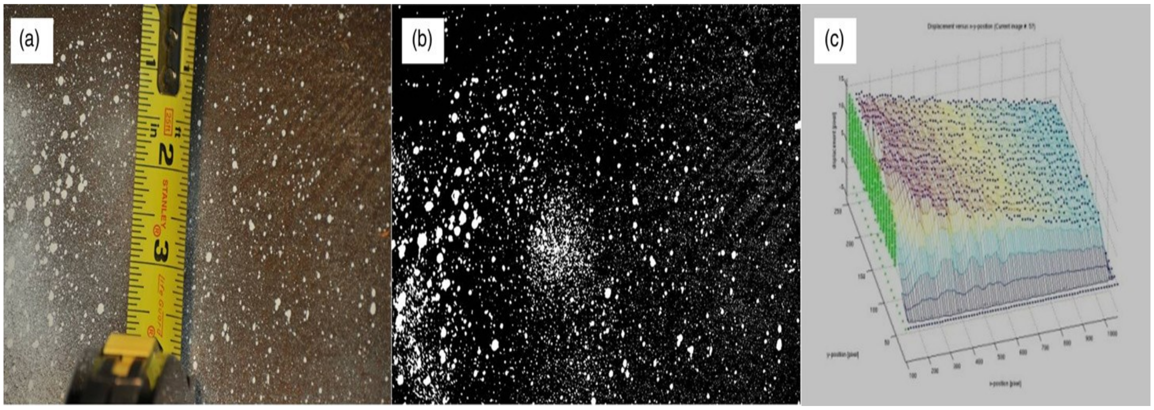


Figure 2-12 Using DIC in finding the displacement response of an I-Beam (Vaghefi et al. 2011).

DIC has applications in detecting surface defects such scaling, spalling, and cracks. Adhikari et al. 2012 have proposed a model that is capable of detecting surface portion loss (scaling) of concrete. In their study, digital camera and artificial neural network (ANN) were utilized for defects detection and condition rating. ANN was used to identify locations of defects. ANN was also utilized to characterize defects and determine their depth based on 7 attributes from image processing. A back propagation ANN model was then developed to model the condition state rating. Another study by Adhikari et al. 2013 has proposed a model to detect surface cracks on decks using digital image processing. Spalls and cracks have been automatically extracted from digital images taken in various cases. The results were satisfactory. The proposed model is expected to eliminate subjectivity of the results in current practice. Condition ratings were calculated based on the areas of the defects as a percentage of the area of the whole inspected element. However, the study was only limited to few types of surface defects (spalling and cracks). Image calibration is not fully automated because scaling factors have to be determined for each image separately.

2.4.8 Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is a well-known non-destructive technique. It can also be considered as a remote sensing technology as well as it has the advantage of acquiring data from a distance. GPRs can be air-coupled which means they don't require physical contact with the inspected object and they can also be mounted on high-speed vehicles for faster inspection (Gucunski et al. 2103). The GPR system consists of three main units, the radar antenna, the control unit, and the display unit. The control unit generates the electromagnetic wave pulses and transmits them through the antenna to the inspected object. The transmitted waves will penetrate through the object. A portion of the waves will be reflected back to the antenna and the other portion will continue penetrating until they diminish. Reflection of the waves is caused by the different dielectric properties of the materials such as reinforcing rebars, air, moisture, and any other anomalies. The reflected waves will be received by the antenna and sent back to the control unit for processing and storage. The processed data will be displayed in the display unit (Gucunski et al. 2013, Wisconsin Department of Transportation 2011).

Several approaches exist in interpreting GPR data. The two main procedures are the numerical method and the visual method. The numerical is the standard method as specified by ASTM D6087-08 2008. When the data collection is done, an amplitude value will be measured at standard intervals along the GPR profile. The amplitude values will be mapped together, and the variations among values will be used to understand the current state of the inspected structure. The results will be presented as maps of amplitude variations with coloured contour lines. The visual method relies on the experience of the analyst. The analyst will define the locations of signal attenuation. The analyst will take into consideration several factors that might affect the signal produced in order to come with precise results. Such factors are reflection amplitudes at the reinforcing bars, at the bottom of the slab, surface anomalies, variations in apparent slab thickness, etc. After that, results will be presented in maps. The numerical method is used in favour of the visual method because of two reasons. The first is that it is faster as it is all automated and does not rely on the analyst experience. The second is that it is considered a quantitative approach, which yields less subjective results. One of the disadvantages of implementing the numerical method is that this procedure ignores more than 80% of the information included in each GPR profile because GPR is an imaging tool (Tarussov et al. 2013). Figure 2-13 shows a typical GPR being used in bridge inspection (Gucunski et al. 2013).

Researchers used GPR and concluded that GPR's main applications are evaluation of the deck thickness, measurement of the concrete cover and rebar configuration, characterization of delamination potential, characterization of concrete deterioration, description of concrete as a corrosive environment, and estimation of concrete properties (Gucunski et al. 2013). According to Department of Transportations, GPR can be used for bridge deck condition evaluation, overlay thickness, voiding under bridge approach slabs, reinforcing steel location, foundation investigation, and underwater profiling (Wisconsin Department of Transportation 2011).

Figure 2-13 GPR unit (Gucunski et al. 2013)

2.4.9 Remote Sensing Technologies Applications

Applications are found out from the literature and listed for each of the technologies. As a result, selecting the best candidate technology will be based on how easy is implementing it. Table 2-9 is summarizing the proven applications of each of the technologies.

Table 2-9 Remote sensing technologies applications

Technology	Reference	Applications
Thermal IR	Vaghefi et al. 2011	Detecting subsurface delamination.
	Wisconsin Department of Transportation 2011	Detecting delamination.
	Washer et al. 2010	Detecting subsurface delamination.
	Gucunski et al. 2013	Voids, cracks, and delamination.

Technology	Reference	Applications
BVRCS	Ahlborn et al. 2013	Tagging photos to their locations.
	Endsley et al. 2012	Measuring surface problems such as cracks, spalls, and scaling.
SAR	Ahlborn et al. 2013	Calculating bridge settelments using InSAR for two railroad bridges in Pueblo, Colorado. And a road bridge near Brimley, MI.
	Kharkovsky et al. 2011	Detecting and evaluating corrosion in steel rebars embedded in reinforced cement-based (mortar) samples.
LiDAR	Ahlborn et al. 2013	Generating a 3D model of a bridge deck, then determining %spall using algorithm used in 3DOBS.
	Chen et al. 2011	Detecting surface damages on bridges, mass loss, and load testing.
	Laefer et al. 2009	Determining crack thickness.
3DOBS	Ahlborn et al. 2013	Detecting surface spalls and bridge deck roughness.
	Endsley et al. 2012	Calculating surface spalls, scaling, and crack patterns.
	Ahlborn et al. 2012	Detecting surface spalls and bridge deck roughness.
DIC	Ahlborn et al. 2013	Measuring beam displacement in laboratory. Measuring bridge displacement.
GPR	Gucunski et al. 2013	Evaluating deck thickness. Measuring concrete cover and rebar configurations. Estimating concrete properties.
	Wisconsin Department of Transportation 2011	Evaluating bridge deck condition, overlay thickness, voiding under bridge approach slabs, and reinforcing steel location.

2.5 INTEGRATED SYSTEMS

Different technologies are being utilized to improve bridge condition assessment process and to identify extent of defects. There is no all-in-one technology that has the ability of generating all the required information regarding the condition state of bridge elements. As a result, integrating more than one technology in one system can improve outcomes of the inspection process.

2.5.1 Integrated System of Remote Sensing Technologies

Remote sensing technologies have wide range of applications. Each has its advantages and limitations. One way to eliminate the limitations is through integrating these technologies. Michigan Tech Transportation Institute (MTTI) and Michigan Tech Research Institute (MTRI) collaborated with the Center for Automotive Research (CAR) and the Michigan Department of Transportation (MDOT) in a project aimed to integrate remote sensing technologies in one system. The project developed a remotely sensed bridge condition signature that will enhance the bridge inspection and augment the asset management programs by assessing in the decision making process and prioritizing critical bridges. The developed system consisted of ten remote sensing technologies. Namely:

- Three Dimensional Optical Bridge-evaluation System (3DOBS)
- Bridge Viewer Remote Camera System (BVCRS)
- GigaPan System (GigaPan)
- Terrestrial Light Detecting and Ranging (LiDAR)

- Thermal Infrared Imagery (Thermal IR)
- Digital Image Correlation (DIC)
- Ultra Wide Band Imaging Radio Detection and Raging System (UWBIRS)
- Synthetic Aperture Radio Detection and Ranging (SAR)
- Interferometric Synthetic Aperture Radio Detection and Ranging (InSAR)
- Multispectral Satellite Imagery (MSI)

All the technologies have been applied and their results were all integrated and presented in one system. They were also integrated with a decision support system that uses the collected data as an input in the decision process. The resulted bridge signature can be used to rank bridges based on the priority of needed actions such as maintenance and rehabilitation. The system provides the Departments of Transportations the ability to perform inspection in a faster manner and the possibility of performing more frequent inspections than the standard twice a year. It also provides bridge managers the ability to assess condition of bridges remotely without the need to visit the inspected bridge and managing the related traffic disruption and lane closure. In addition, the system provides the inspection teams with preliminary condition data provided by the sensors, this will let the teams to focus on trouble spots immediately. Finally, a computer-based Decision Support System with web interface software tool was developed. This system integrates all the data from the various sensors, the historical data, and the inspection data of each bridge. By monitoring the health signature of each bridge and how they change over time will aid the bridge asset managers in prioritizing critical bridges (Ahlborn et al. 2013).

2.5.2 IR and GPR Integration Applications

Integrating IR and GPR can produce information on surface and subsurface defects simultaneously. Hing and Halabe 2010 studied the possibility of integrating the use of IR and GPR on glass fiber-reinforced polymer (GFRP) bridge decks. They have studied such type of decks, as they are becoming an alternative to traditional bridge decks. The main reason of their study is to validate the use of GPR in detecting water-filled void within the material, and the ability of IR in detecting air-filled voids in the same material. Using a standard 1.5 GHz GPR and a radiometric IR camera, the study concluded the effectives of their usage. GPR was confirmed to be able to detect moisture filled voids and had the promise to be able to detect defects in bottom flange at 10 cm depth. IR had shown the ability of detecting both water-filled and air-filled voids within the top layer of the deck. The authors remarked that the integration of the technologies would provide a more detailed and accurate condition assessment.

Shroff 2008 has studied the application of IR and GPR together for bridge deck inspection. The system consisted of an Infrared sensor camera and a GPR antenna, both mounted on a vehicle that can move over the bridge with a speed of 10-20 mph. The integration was in mounting both technologies on the same vehicle. The two methods will collect data, data analysis will be done separately, and finally results will be presented to cover the condition of the deck. The author stated that the combination of GPR and IR have the ability of detecting half- and full-depth concrete delamination, determine their depth, and plan all the conductive area of the bridge and detect corrosion in those sections. The GPR/IR inspection was performed on the Robert Mosses Causeway, and 54 cores were taken. The results of the GPR/IR scans and the cores showed good correlation.

Another study by Moropoulou et al. 2002 has shown the potential of using GPR and IR for airport pavement assessment. Their main purpose was to study the usability of IR and GPR in assessing the condition of airport pavement condition. The two technologies were applied in the International Airport of Athens in Greece. The findings of the study have shown that the IR had the ability of detecting defects. But IR exhibited a limitation in identifying the depth and thickness of the defects. The GPR on the other hand, demonstrated the ability of detecting the defects' dimensions and measure their thickness and depth. The authors concluded that IR and GPR could be utilized together to assess condition of airport pavement efficiently.

2.6 ARCGIS

This Section reviews the concept of ArcGIS and its applications in infrastructure management and bridge condition assessment. ArcGIS can be integrated with remote sensing technologies as an enhanced medium for data analysis, presentation, and reporting.

2.6.1 Overview of ArcGIS

ArcGIS is a software product from ESRI (Environmental Systems Research Institute, Inc.) for the Geographic Information System (GIS). GIS was basically developed to replace the traditional way of studying maps and geographic globes into a more sophisticated computer system. GIS is the collection of all the maps, globes, and computer models along with tools for data analysis. GIS lets the user study every possible map with detailed information such as land, elevation, climate zone, population density, per capita income… etc. A GIS map is made of layers that contain all the information. Layers can be oceans, countries, cities, rivers, and lakes. Each layer may contain specific features and information. For instance, cities layer contains several cities and each city is a feature. Features in GIS have different properties including surfaces, sizes, numeric values, locations, and linked to information (Ormsby 2009).

Bridge inspection can be enhanced by introducing ArcGIS software for data storage, analysis, and reporting. ArcGIS is used to create and share interactive maps. In bridge management layers can be designed to include bridges and inspection data. These layers can be maps for the inspected bridge, maps of the results of each technology, and additional maps from more technologies if needed. These layers are used to illustrate information as visual maps of results. In addition, multiple users can use the ArcGIS simultaneously and data can be streamed into the system continuously.

2.6.2 ArcGIS Applications in Infrastructure Management

In the past two decades, GIS had emerged as a concept and had some applications in bridge management, while the use of ArcGIS, which is one of the popularly known GIS software, is quite new. For instance, Johnson and Goldman

1990 introduced the use of GIS for infrastructure management. The paper was focusing on the advantages of utilizing GIS for infrastructure management as GIS has the abilities of storing and analyzing spatial information, providing visual indications by using different colors, and overlaying different maps. GIS can be beneficial for bridge inspection. Hammad et al. 2003 proposed a system called LBC-Infra (Location-Based Computing Infrastructure) that aid in bridge inspection. The main focus of this system is to integrate wireless communication with spatial databases, tracking technologies, and mobile computing, such that the bridge inspector can use a laser pointer to point on a part of a bridge. Based on the pointer location and orientation, and connecting that to the databases using a mobile computing device, information regarding the specified structural element can be retrieved at the spot. Further, the bridge inspector can connect with other personnel who are not on sight through wireless communication. Another application of GIS in bridge condition assessment is done by Jiang and Zhang 2009. They have developed a WEBGIS-based quality inspection and evaluation system for bridges. Their proposed system can enhance the inspection process. The inspection plan will be pre-defined in the system. The inspectors are not supposed to study the bridge before the on-site inspection, they are only required to inspect the specified parts and elements that are retrieved from the databases and shown in the system. The system will do the required calculations and produce a condition rating. In other words, the bridge inspector role will be only performing the data measurement on site and the system will do the rest. The final results will be a score for the bridge in the network and a rating for its condition.

ArcGIS has the ability to define layers and include several inspection results from different technologies which makes this software a means of data analysis and/or reporting. Analysis can be performed in ArcGIS by defining algorithms to let the software perform calculations and present the analysis required. Data reporting is also a great feature of ArcGIS, as it shows the results in maps and has the ability of sharing results through its server, so that live updates from several users can be made. Vaghefi et al. 2013 have utilized ArcGIS to analyze and report inspections results. In their study, Thermal Infrared and 3D Optical Bridge Evaluation System (3DOBS) were used to perform bridge inspection. Results obtained from IR were enough to detect subsurface defects, such as delamination, similar to chain drag test. 3DOBS was able to detect surface defects such as spalls. Both of the results were integrated and presented in ArcGIS. ArcGIS was used to perform data analysis on the inspection results as well. The authors defined an algorithm to calculate the number of pixels that contribute to defective areas. The final results were presented in ArcGIS as maps of surface and subsurface defects, and as percentages of defective areas. Another application of ArcGIS for bridge condition assessment is the work of Wu et al. 2012. The authors developed a model for bridges and roads management system that incorporates ArcGIS. The proposed system is meant to improve the current practice in which data management was done on papers and data analysis was done by statistical methods, and lacks spatial analysis and geographic analysis. ArcGIS alongside with Visual Basic 2005 were used in their model to visualize and analyze the spatial data of roads and bridges infrastructure. The model has several functions such as data storage and management, inquiry, statistics, thematic map representation, spatial analysis, real-time monitoring of road, and monitoring and warning of well cover so on. The authors concluded that the proposed system will aid in improving infrastructure management more effectively.

CHAPTER 3 COMPARATIVE STUDY OF REMOTE SENSING TECHNOLOGIES

3.1 INTRODUCTION

This chapter presents the findings of a comparative study conducted on the seven remote sensing technologies discussed in Section 2.4. The main objective of the comparative study is to provide a flexible model for professionals in the field of concrete bridge inspection and condition assessment that can recommend the most suitable technologies for implementation based on project objectives and end-user preferences. Detailed information on criteria used in the developed model is presented as well as an example showing how the model can be used and how it functions.

3.2 ANALYSIS OF REMOTE SENSING TECHNOLOGIES

To investigate the potential of developing a system for bridge inspection using remote sensing technologies, a comparative study is carried out in this research based on a set of flexible criteria. The proposed criteria are flexible in the sense that the end-user has the ability of adding, removing, and/or adjusting the criteria and/or their relative weights. Thus, based on the end-user preferences, the technologies would be ranked and the most suitable one can be selected. The main criteria used in the study are:

- Capabilities of each technology
- Constraints on usage
- Cost

- Ease of implementation.

The above criteria were identified based on literature review and consultation with a senior expert (Yaghi et al. 2014). A detailed breakdown of the criteria is provided in Figure 3-1 and a brief description of the criteria is given in the following four Sections.

3.2.1 Capabilities of Each Technology

The capabilities refer to the ability of the technology in detecting anomalies. Defects are occurring in concrete because of poor placement of concrete, use of non-durable concrete mixture, or harsh environment where the concrete is placed (OSIM 2000). One important component of a bridge is its deck. Detecting bridge deck defects and resolving them are essential steps to preserve the planned useful life of the bridge as bridge decks have the shortest useful life compared to its other elements (Washer 2003). As a result, bridge deck has a high potential for benefiting from applying remote sensing technologies in condition assessment and will be the focus of the current research. The most common bridge deck defects found in the literature are: scaling, corrosion of reinforcements, delamination, spalling, cracking, expansion joints problems, and changes in bridge length and settlement (Ahlborn et al. 2010, Washer et al. 2010, OSIM 2000). In this chapter the seven defects will be referred to as D1, D2, D3, D4, D5, D6, and D7 respectively. Tables 3-1 and 3-2 summarize the different types of defects and their corresponding technology that has the potential ability of its detection based on the information found in the literature.

Table 3-1 Deck surface defects

	D1	D2	D3	D4	D5	D6	D7
Thermal IR	✓		✓	✓	✓	✓	
BVRCS	✓		✓	✓	✓	✓	
SAR							✓
LiDAR	✓		✓	✓	✓	✓	
3DOBS			✓	✓			
DIC							✓
GPR							

Table 3-2 Deck subsurface defects

	D1	D2	D3	D4	D5	D6	D7
Thermal IR	✓		✓	✓			
BVRCS							
SAR		✓					
LiDAR							
3DOBS							
DIC							
GPR	✓	✓	✓	✓			

3.2.2 Constraints on Usage

Each technology has its own constraints on usage based on the different environmental and physical constraints. Some technologies can be used in all weather conditions while others can be used only under specific conditions. In this research, constraints on usage are related to the applicability of each technology within the different timing of the day and to the different vehicle speed levels at which the technologies can be used. Table 3-3 summarizes each technology and its constraints on usage (Ahlborn et al. 2013, Vaghefi et al. 2012, Kharkovsky et al. 2011, Wisconsin Department of Transportation 2011).

Table 3-3 Constraints on usage

Technology	Day and night usage	Speed of vehicle
Thermal IR	All day long	8 -10 mph (fast)
BVRCS	Daylight	< 5 mph (slow)
SAR	All day long	*
LiDAR	All day long	35 – 50 mph (fast)
3DOBS	Daylight	< 2 mph (slow)
DIC	Daylight	10 mph (fast)
GPR	All day long	< 5 mph (slow)

* For bridge settlement measurements, SAR is mounted in aircrafts or satellites. For corrosion detection, SAR has been used in stationary position.

3.2.3 Cost

Cost is an essential factor in infrastructure management since departments of transpiration are operating within limited budgets. Cost data for five of the remote sensing technologies is summarized in Table 3-4 as captured from a recent report by Hong et al. 2012. The SAR technology was evaluated recently to estimate bridge settlements and length changes (Ahlborn et al. 2013). It has not been applied for subsurface condition assessment of concrete bridges to this date. As a result, cost data of applying this technology is not available in the literature. The cost of GPR can be obtained from GSSI Inc.

Table 3-4 Cost data (Hong et al. 2012)

Technology	Data Collection system	Labor cost (per bridge)	Analyzing results
Thermal IR	$30,000	$450	$770
BVRCS	$7000	$100	$120
SAR	-	-	-

Technology	Data Collection system	Labor cost (per bridge)	Analyzing results
LiDAR	$500,000	$850	$920
3DOBS	$34,000	$150	$151
DIC	$5500	$450	$770
GPR	-	-	-

3.2.4 Ease of Implementation

Ease of implantation can be implied from the nature of the process of applying each technology and the related procedures. To facilitate evaluating the remote sensing technologies, ease of implementation criterion is divided into: the availability of hardware or software, time required for implementation, and the requirement of a trained crew for application. Table 3-5 summarizes ease of implementation data as extracted from the literature (Ahlborn et al. 2013, Vaghefi et al. 2012, Vaghefi et al. 2011, Wisconsin Department of Transportation 2011, Washer et al. 2010).

Table 3-5 Ease of implementation

Technology	Procedure	Hardware/software	Time	Trained crew
Thermal IR	IR cameras are mounted on vehicles. Images are captured while the vehicle is moving over the bridge. Images are then analyzed using specialized software.	IR Camera Vehicle Commercially available software	Slow process	Yes
BVRCS	Two cameras are	Two Cameras	Less	Yes

Technology	Procedure	Hardware/software	Time	Trained crew
	mounted on a vehicle. Photos will be captured and will be location-tagged.	Vehicle Commercially available software	than 30 minutes	
SAR	Antennas are mounted to an airplane or a spacecraft; electromagnetic waves are transmitted and received, and then analyzed for model development.	SAR Antenna Airplane, satellite, or a moving device Commercially available software	-	Yes
LiDAR	LiDAR sensors, scanners, or both are used to acquire data. Software will be utilized to analyze the data. Mobile LiDAR works at a speed of 35-50 MPH.	Sensor mounted in an aircraft, or Scanner mounted on a tripod, or Sensors and scanners mounted on a vehicle. Available software compatible with each hardware used	Slow process	Yes
3DOBS	Cameras are mounted on vehicles or satellites. Photos will be captured and analyzed to generate 3D model.	High resolution Cameras Vehicles or satellites Commercially available software	Less than 30 minutes	Yes
DIC	Taking photos of the same object with time difference. Then, analyzing the photos with the soft-ware.	Camera Commercially available software	Slow process	Yes
GPR	Radar antenna will be moving over the	GPR Antenna Carrying cart	Slow for	Yes

Technology	Procedure	Hardware/software	Time	Trained crew
	bridge to collect profiles for each pass over the bridge. The profiles will be analyzed later for condition assessment.	or Carrying vehicle Commercially available software	ground coupled Fast for air coupled	

3.2.5 Model

Figure 3-1 shows the different criteria set for the study. The end-user will set the different weights between the main criteria and sub-criteria. To ensure flexibility, a weight of zero can be selected to eliminate any criterion from the study and the adopted evaluation criteria are assigned pair-wise relative importance weights based on Saaty's rating scale shown in Table 3-6 (Saaty 1994). Figure 3-2 is an example on how the pair-wise comparison between the different criteria is defined. In the model, each cell has a drop-down list of the relative weights. The end-user can choose the different weights as shown in Figure 3-2. For instance, if cost criterion has very strong importance preference over the technology capabilities criterion, then, the intensity of importance between cost and capabilities is 7 and between capabilities and cost is 1/7. This procedure is repeated to cover all the criteria under consideration.

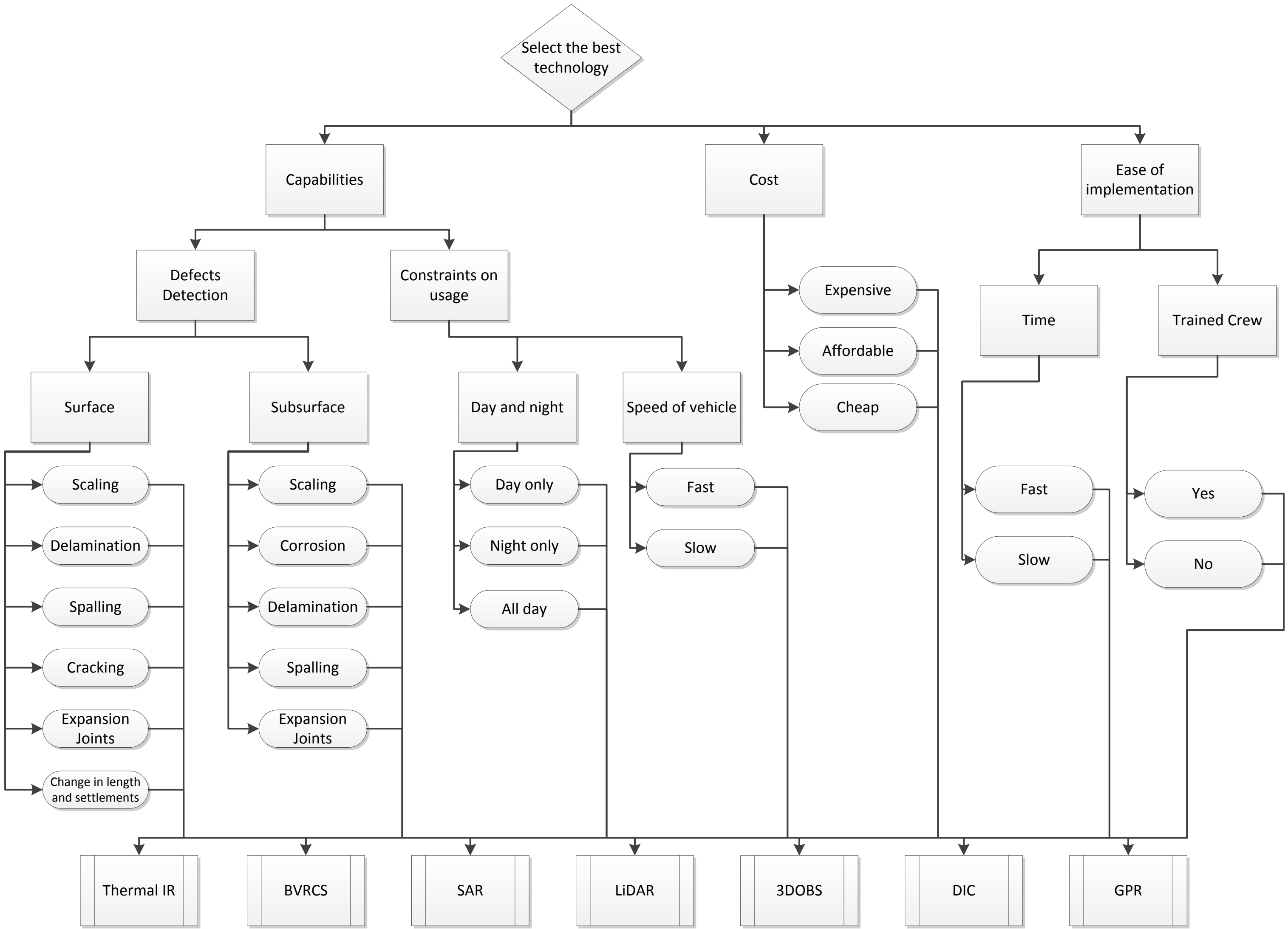


Figure 3-1 Criteria adopted for the comparative study

Table 3-6 Saaty rating scale

Intensity of importance	Definition	Explanation
1	Equal importance	Both attributes are equally important with respect to the objective
3	Moderate importance	One attribute has moderate importance over the other attribute
5	Strong importance	One attribute has strong importance over the other attribute
7	Very strong importance	One attribute has very strong importance over the other attribute
9	Extreme importance	One attribute has extreme importance over the other attribute
2,4,6,8	Intermediate values	Intermediate values to compromise the importance

3.2.5.1 Model Example

After assigning the relative weights between the criteria, the model assigns a weight for all the criteria and sub-criteria based on the pairwise comparisons by using the Eigenvector approach adopted in the Analytic Hierarchy Process developed by Saaty 1994. Finally, the model generates a score for each technology. The technology with the highest score is recommended to be used. The score is reflecting both the data extracted from the literature in Tables 3-1, 3-2, 3-3, 3-4, and 3-5 and the weights assigned from the pairwise comparisons. Figure 3-3 shows a hypothetical example to evaluate the remote sensing technologies based on capabilities criterion and constraints on usage sub-criterion. The weights shown in the example in Figure 3-2 are hypothetical. The questionnaire survey was not designed to get the relative weights used in this developed model. That is because it is intended to keep the model flexible and adaptable to account for different projects needs and end-user preferences.

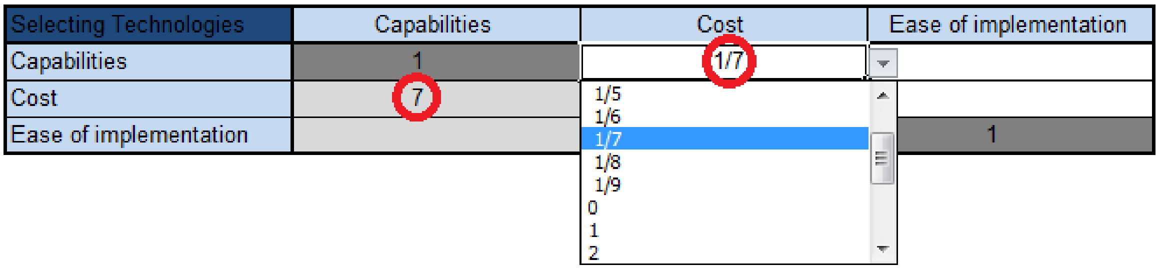


Figure 3-2 Proposed model pairwise comparisons

For example, Thermal IR can be used all day long and can be mounted on fast vehicles while BVRCES can be used only during day time and can be mounted on slow vehicles. Thus, IR score would be equal to 0.6x0.6x0.3x0.5 + 0.7x0.4x0.3x0.5 = 0.096, and BVRCES equals to 0.2x0.6x0.3x0.5 + 0.3x0.4x0.3x0.5 = 0.036.

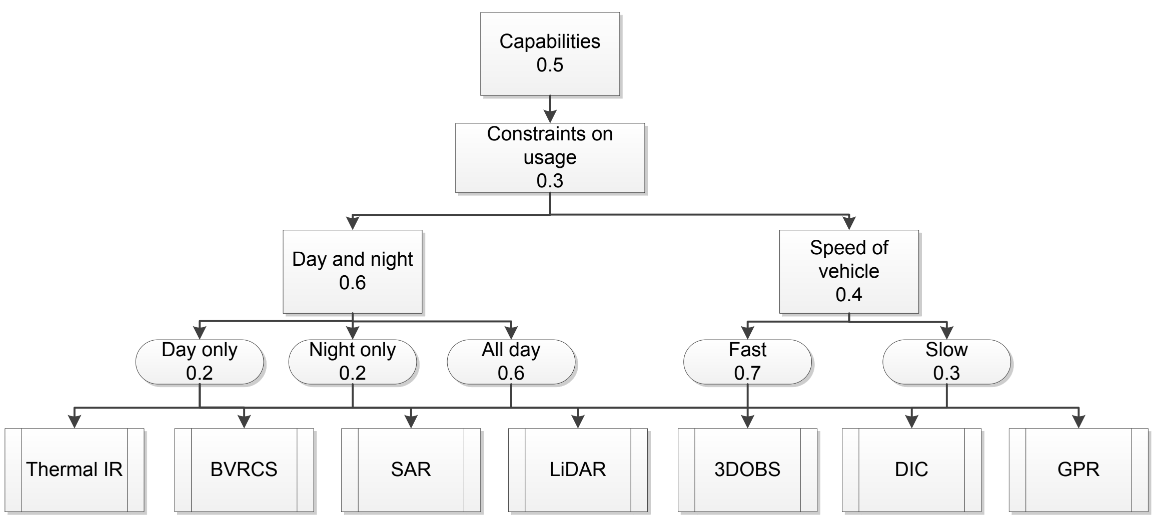


Figure 3-3 Model example

3.2.6 Results Analysis

A comparative study was conducted on seven remote sensing technologies based on a set of flexible criteria. The model reveals that thermal IR shows a great potential in detecting wide range of surface and subsurface defects. SAR system demonstrates a potential to detect corrosion in rebars. GPR shows a great potential in detection subsurface defects such as delamination, corrosion, and scaling. Unlike other technologies considered in the study, LiDAR can be used all day long and nearly at highway speed but this technology has higher cost than thermal IR. BVRCS and 3DOBS are relatively faster to deploy and utilize; their data processing time is less than 30 minutes, while others can exceed one day. Selection of the most suitable inspection technology requires trade-offs among project objectives and depends on the required purpose of the condition assessment and the project overall conditions. A model similar to that presented in Chapter 3 is expected to be useful in this selection process. Practitioners interested in evaluating these technologies can use the model by choosing a specific set of criteria and assigning their relative importance based on project objectives.

3.2.7 Limitations of the Comparative Study

The proposed system has several limitations. Below are the main limitations of the proposed comparative study.

- The model is limited to four multi-attributed criteria.
- The model is limited to seven remote sensing technologies.
- The model is limited to technologies that can be used in concrete bridge inspection only.

CHAPTER 4 HYBRID SYSTEM FOR BRIDGE CONDITION ASSESSMENT

4.1 INTRODUCTION

The main objective of this chapter is to present the developments made to integrate inspection results of GPR and IR to enhance the accuracy of interpreting thermal images and radar profiles. As well, to utilize that integration in improving the visualization of the condition of inspected bridges.

4.2 HYBRID SYSTEM OF TECHNOLOGIES

Delamination can be identified as high temperature areas in thermal images and as zones with signal attenuation in GPR profiles. But high temperature in thermal images is not always due to delamination. High temperature areas in thermal images could be caused by different environmental conditions or different materials properties and not necessarily because of delamination (Washer et al. 2010). In addition, signal attenuation in GPR profiles is not always caused by delamination as other factors can influence the profile such as different bar diameters, moisture, etc. (Tarussov et al. 2013). Therefore, as the main factors affecting the results of each technology are different and by eliminating areas that have either of high temperature or signal attenuation, it is likely to detect delamination more accurately by identifying locations at which both high temperature and signal attenuation occur. The output from these technologies will be used in ArcGIS. ArcGIS will be used to present the results. The final results produced will be in the form of maps of detected defects that are geo-referenced. This integration has the potential to give bridge engineers more understanding of the condition of the bridge when compared to reading reports.

4.2.1 Thermal IR

The concept of IR thermography was discussed in Section 2.4.2. ASTM D4788-03 2003 describes the test method, the environmental conditions, and the equipment needed to detect subsurface defects. To implement IR procedure, a grid on the inspected area should be pre-defined. The grid specifies a certain area to be covered in each thermal image. This procedure will facilitate the process of building the thermograph map of the inspected bridge as edges of each image area defined in the grid and are numbered. The edges of each square in the grid will be specified on the surface of the inspected bridge as well. A thermal image will be taken covering the area bounded by the edges of each square. The numbers are used to reference each image to its associated location on the bridge deck. Therefore, a thermograph map can be built by joining the edges of each image on its corresponding location. Defining such areas will ease the process of importing the map into ArcGIS and define its coordinates. Regular images will also be taken covering the same areas that IR images cover. This will have two advantages. One advantage is that it will aid in interpreting each thermal image. Figure 4-1 is an example where it shows that in A&B a high temperature area in the thermal image might reflect a delaminated area. While, in C&D the higher temperature area does not reflect a delaminated area, it rather reflects a dry area surrounded by a wet area on the surface, which can be clearly seen in C. Another advantage is that regular images will help in building a regular map of the bridge to be imported to ArcGIS later on.

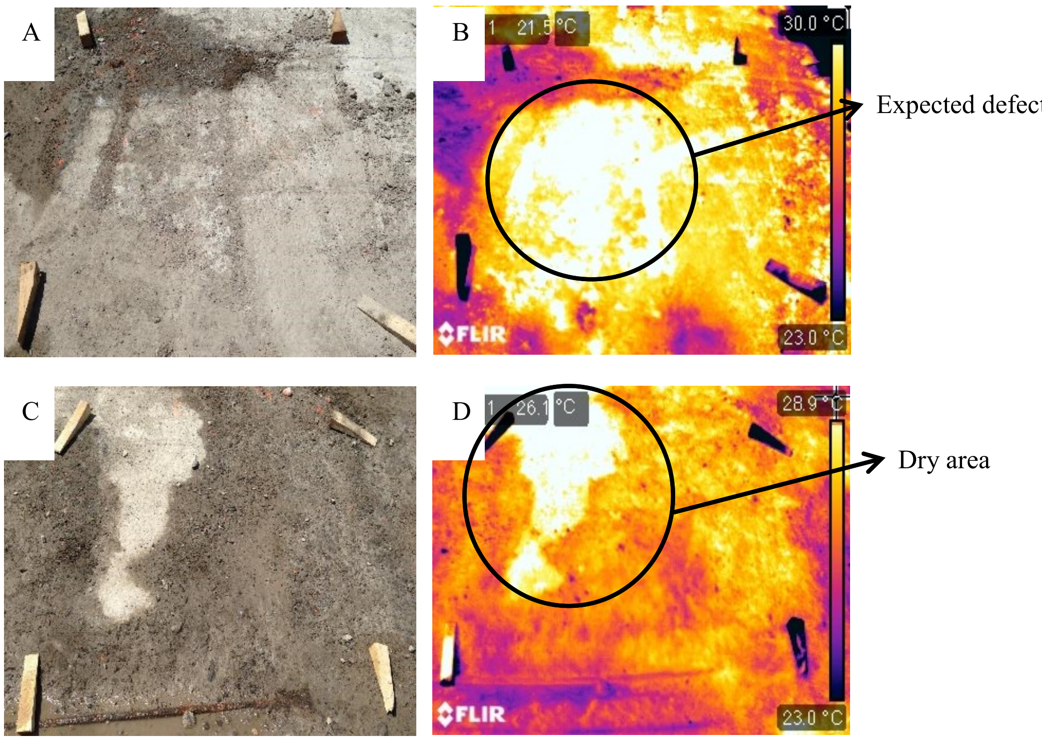


Figure 4-1 A&B high temperature might refer to a potential defect. C&D high temperature refers to a dry area not a delaminated area

After studying the IR images, all the images will be linked together. The edges of each area shown in the IR picture will be joined together to form the thermograph map. The thermograph map will consist of series of thermal images placed next to each other based on the edges of each area and their numbers specified in the grid. Next, all the areas that show high temperature and can be a potential delamination will be marked on top of the map. Therefore, such locations of high temperature will be corresponding to their actual locations on the bridge deck. Figure 4-2 shows a hypothetical example of a 4x5 grid of images. The red splines are drawn to refer to the hypothetical locations of potential delamination.

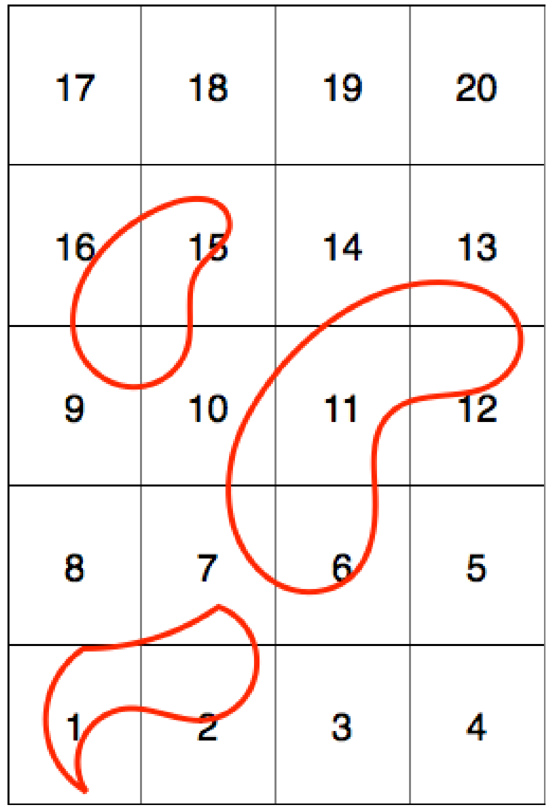


Figure 4-2 A 4x5 grid for thermal images with hypothetical areas of high temperature

4.2.2 GPR

GPR was discussed earlier in Section 2.4.8. The concept of the visual approach will be adopted in this system for two reasons. Firstly, because GPR is mainly used as a locating and an imaging tool which are two of its sole purposes. Secondly, because defining locations of signal attenuation is the basic principle in understanding GPR profiles after which several approaches were being developed (Tarussov et al. 2013). The integration of GPR and IR will help in minimizing the GPR visual method's limitation of slow analyzing process; this will be discussed later in Section 4.2.3.

The first step in implementing GPR is also by pre-defining the grid for the GPR scans. GPR grid is different than the IR grid. The GPR grid consists of lines that define the paths at which each GPR pass will scan. This grid will help in developing the GPR results map later on by linking each pass with its correspondent line in the grid. After that, the bridge will be scanned. The GPR machine will be used to scan all the passes as prescribed in the grid. GPR already uses GPS for coordinates, thus, there is no need to define a procedure for this task. Figure 4-3 is a typical GPR pass result. The red rectangles are manually added to define locations of signal attenuation that might refer to delamination. The distance of the expected delamination from the edge of the pass is shown in the figure in feet. The same procedure of defining rectangles will be repeated on all the rest of the passes. As a result, locations of all the expected defects will be known. Extracting those locations and highlighting them on the GPR grid will be an easy task, as shown in Figure 4-4 a hypothetical case where the locations of signal attenuations are highlighted on the GPR grid map.

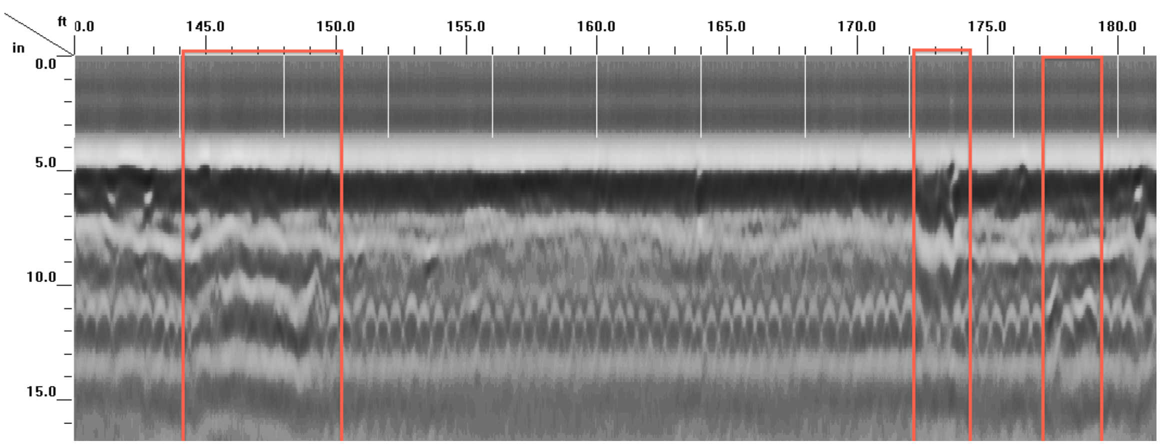


Figure 4-3 GPR scan and potential delamination

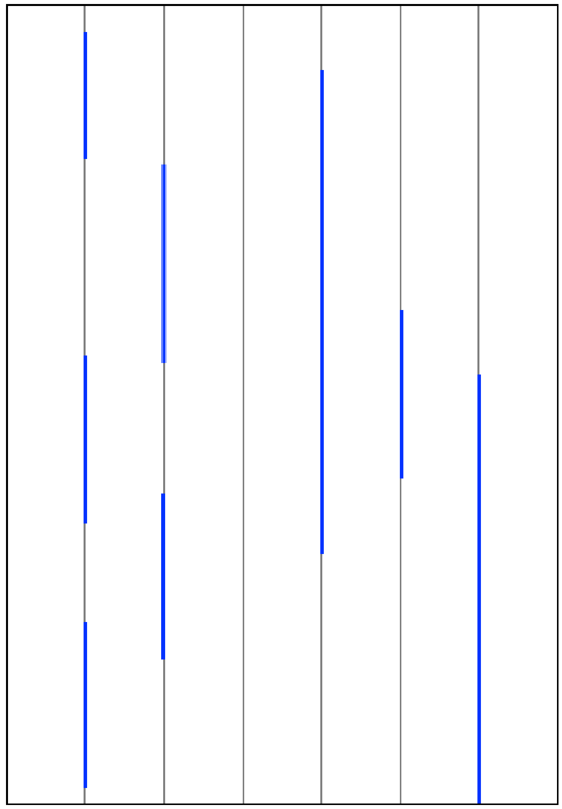


Figure 4-4 Hypothetical highlighted GPR grid

4.2.3 Integrating IR and GPR Results in ArcGIS

One of the key benefits of this integration is that it will overcome some of the limitations of the IR and GPR data interpretation. IR data interpretation is a difficult task as several factors contributes in forming high temperature areas such as environmental conditions, ambient temperature and other factors. GPR data interpretation using the visual approach is considered a slow process because defining the correct locations of delamination requires experience of the data analyst. Integrating the results of both technologies will minimize the effect of each of their limitation. In other words, defining the areas at which both high temperature and signal attenuation occurs will have an advantage. It will likely increase the accuracy of the results, because the factors that harden the understanding of IR results are different than the factors of the GPR. Figure 4-5 illustrates the integration of the hypothetical IR and GPR results maps. In Figure 4-6 the results of each technology are reduced based on the coinciding areas at which IR and GPR potential delamination intersect. This means that the marked areas are expected to be delaminated and the eliminated areas are not expected to be delaminated. The integrated maps will be presented in ArcGIS. The presentation of the maps in ArcGIS will enhance the visualization and presentation of the defects. Defects can be seen on maps on their respective locations on the bridge, as the generated maps are geo-referenced in ArcGIS. Figure 4-7 shows the hypothetical example in ArcGIS.

Finally, condition rating of inspected bridges can be calculated based on the identified defective areas. According to Minnesota Department of Transportation 2013, concrete decks and slabs can be rated based on the areas calculated of defective spots on the deck. Table 4-1 summarizes the condition ratings.

Table 4-1 Condition state based on area defective (Minnesota Department of Transportation 2013)

Condition State	Case description
1	No spalls, delaminations, or temporary patches on top surface
2	Combined areas of defects is 2% or less
3	Combined areas of defects is more than 2% or less than 10%
4	Combined areas of defects is more than 10% or less than 25%
5	Combined areas of defects is more than 25%

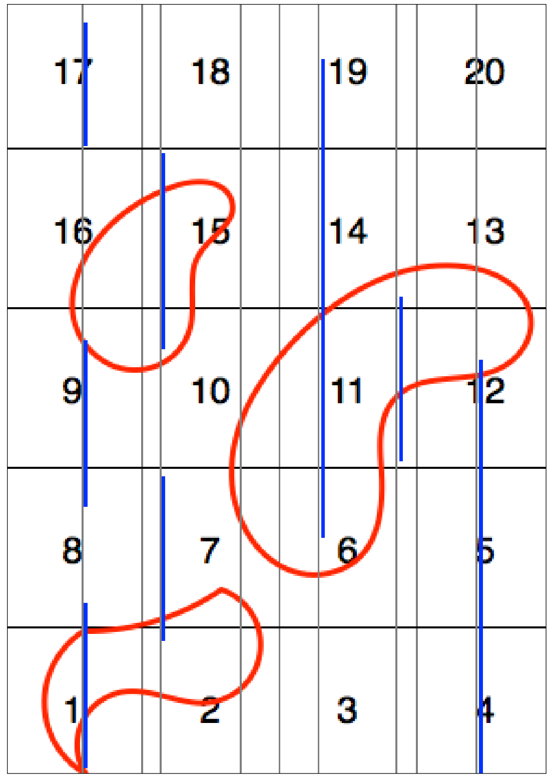


Figure 4-5 Integrating results

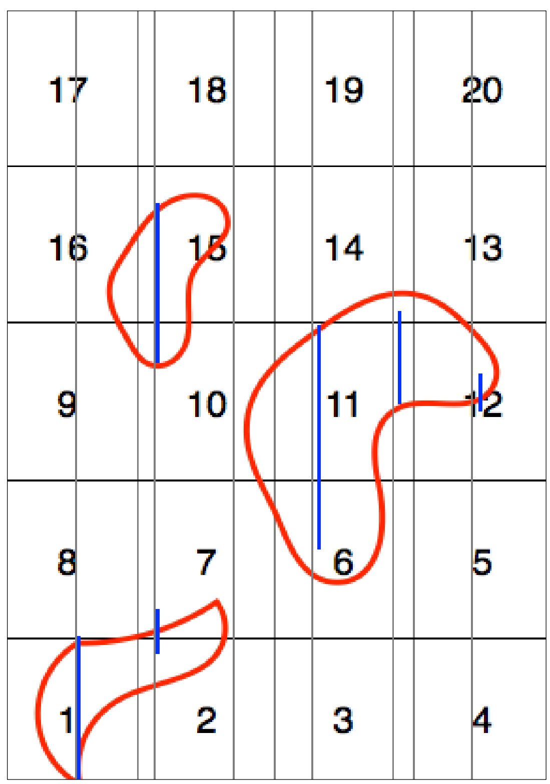


Figure 4-6 Results after elimination

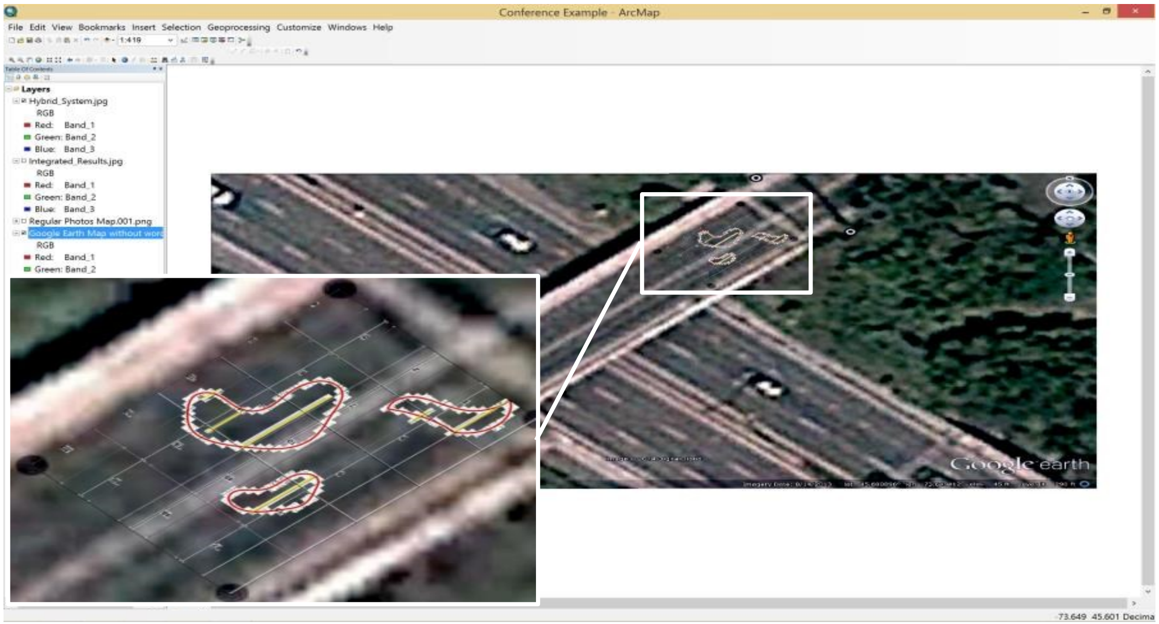


Figure 4-7 Hypothetical Example in ArcGIS

4.3 FIELD IMPLEMENTAION

4.3.1 Overview

The proposed hybrid system was implemented in a case study. The case encompasses 77 square meter section of a concrete bridge located in Laval, north of Montreal, Quebec, Canada. This bridge section was inspected using IR and GPR technologies (see Figure 4-8). The section has dimensions of 7m x 11m. The asphalt layer was removed from the inspected area, so that the inspection can be performed on concrete deck. The same area was also inspected using the hammer sound test. Thus, the results can be compared with those obtained from the hammer sound test. The inspected area was divided by a grid into square areas of 1m x 1m; resulting in a total of 77 squares. This is done to facilitate the use of IR camera and the hammer sound test. Also, another grid of 24 passes at 1 foot width for the GPR scans starts at 1.5 foot from each side of the bridge was defined as shown in Figure 4-9 The grid used for the GPR passes on top of the IR grid, the black circles refer to the edges of each thermal image taken, and the longitudinal lines refer to each GPR pass made.

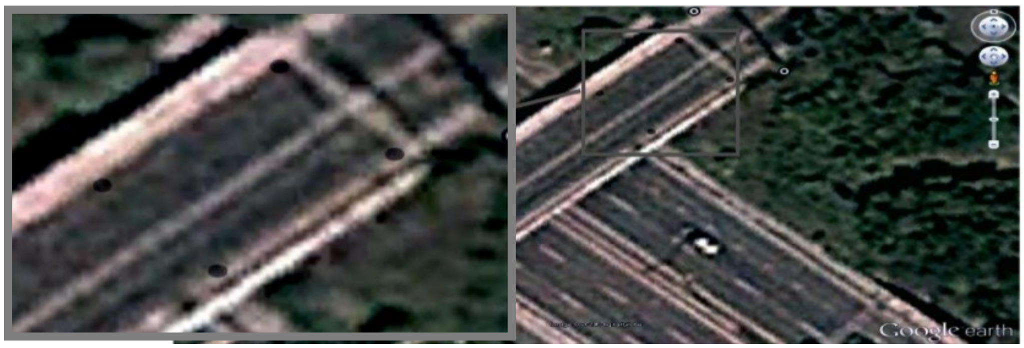


Figure 4-8 The Inspected bridge

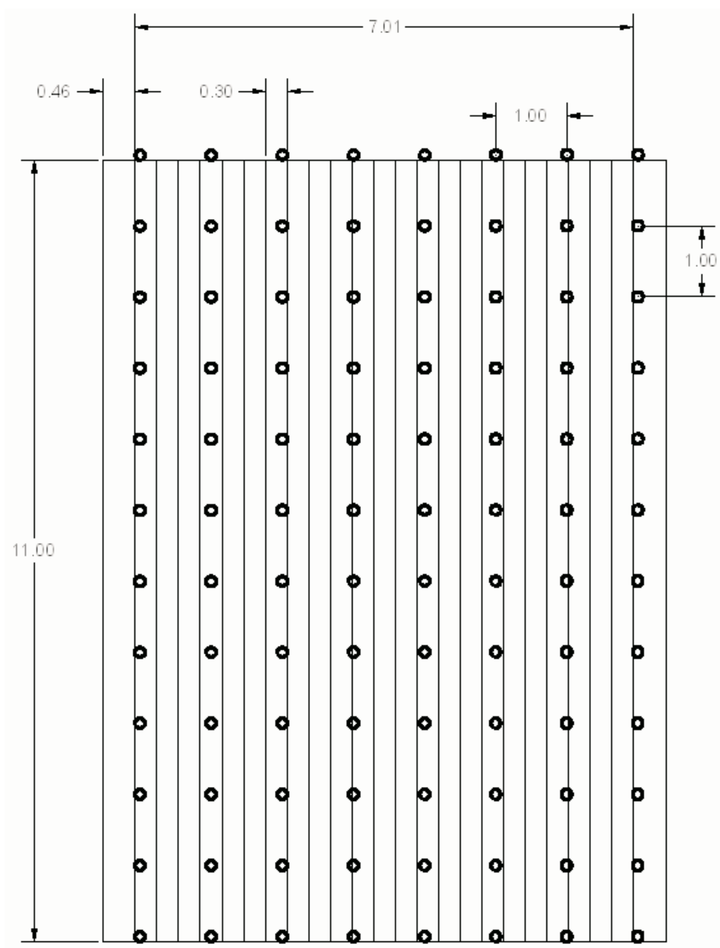


Figure 4-9 IR and GPR grids

4.3.2 Thermal IR Data and Results Analysis

The IR camera used in this inspection is ThermaCAM S60 a product of FLIR Systems. An external lens with 45º angle was used to capture wider images. This camera was used to take thermal images of the 77 defined areas. Wooden pieces were used to determine the edges of each squared area to assist building the maps. As the wood used was of lower temperature than the surrounding surface of the concrete, they appear as dark objects in the thermal images, thus edges of each squared area are defined. Figure 4-1 shows the wooden pieces that define the boundaries of the squared areas. The data processing method was conducted using special software “FLIR Tools” provided by the vendor of the camera. The temperature range for each thermal image was set to be automatically defined. The temperature scale was taking into account the wood temperature, which is in this case not related to the study. Thus, the range of temperatures was slightly adjusted using the software in order to define higher temperature areas that correspond to delamination more precisely. An example of the temperature scale is shown earlier in Figure 4-1-B, it shows that the range is between 19Cº and 35Cº and also shows an expected defect as it appears in higher temperature (brighter color). The scale of temperature is different for each image and is not the same. This is due to different time and environmental conditions at which the images were taken (Vaghefi et al. 2013). This means that the delamination in different images would appear at different temperatures. A thermal infrared map was created from the 77 images. The map was created using software called Keynote on Mac OS 10.9.3. Two of the thermal images, at squares 62 and 63, were missing and could not be retrieved, Figure 4-10. The thermograph map was imported into AutoCAD. Locations of high temperature were defined. Splines were drawn over each area in which the temperature is high. Figure 4-10 shows the thermograph map with areas of high temperatures marked. The marks refer to potential subsurface defects. The thermograph map was removed from the background and the map with the defects in their corresponding locations is shown in Figure 4-13-A.

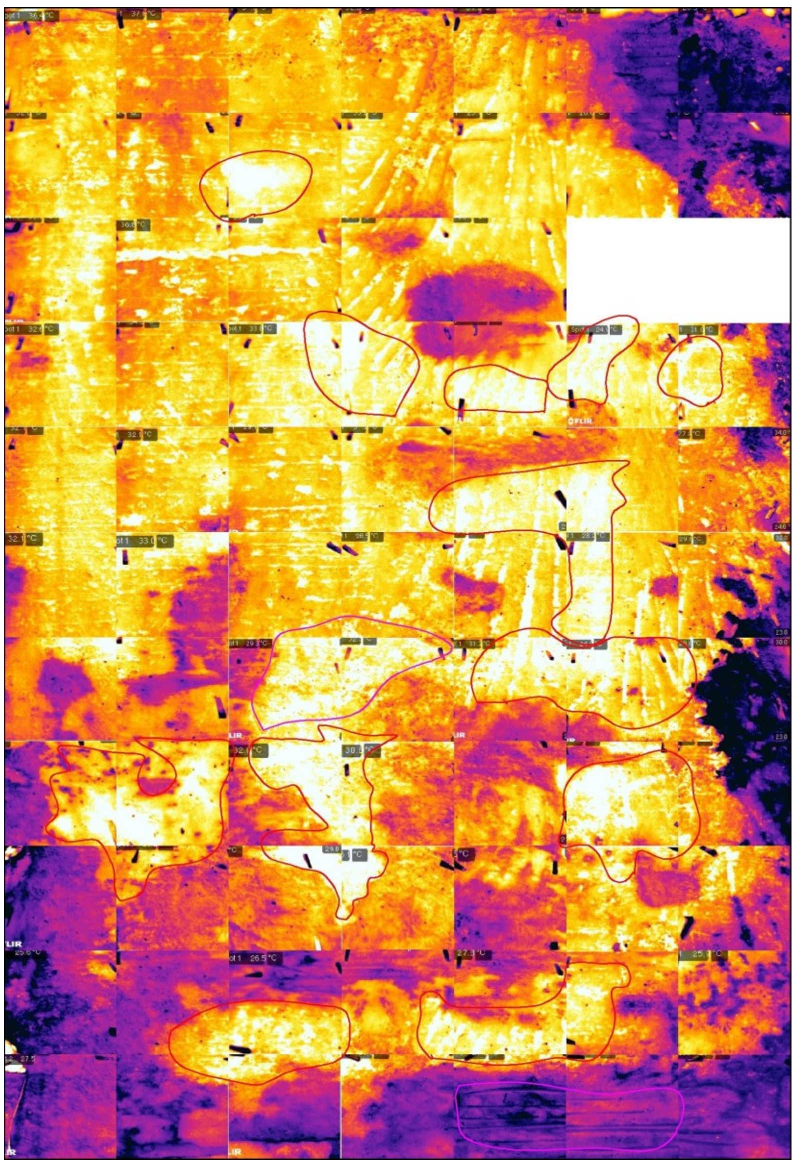


Figure 4-10 Thermograph map with marked areas

4.3.3 GPR Data and Results Analysis

The bridge deck was scanned using GPR equipment. A cart that holds the GPR device provided from GSSI with 1.5 GHz antenna was pushed over the bridge to do the scans. The scan passes were taken at 1.5 feet (0.4572 m) from each side curb, and the scan passes were taken at 1 foot (0.3048 m) spacing as shown previously in Figure 4-9. The whole bridge in the case study was scanned by Kien Dinh, a PhD candidate at Concordia University, as part of his research. A segment of the scans were used in this research that corresponds to the same areas scanned by the IR camera. Thus, the beginning of the profiles in this case starts at 144 ft not zero, because the zero reference was not part of the inspected area of this case study. RADAN software was used to interpret the results. Signal attenuation locations were defined as described earlier in 4.2.2. In Figure 4-11 it shows that signal attenuation occurs from 144 to 150 ft (0 to 1.83m) and from 173 to 177 ft (8.84 to 10.06 m) of the second pass of the GPR scans.

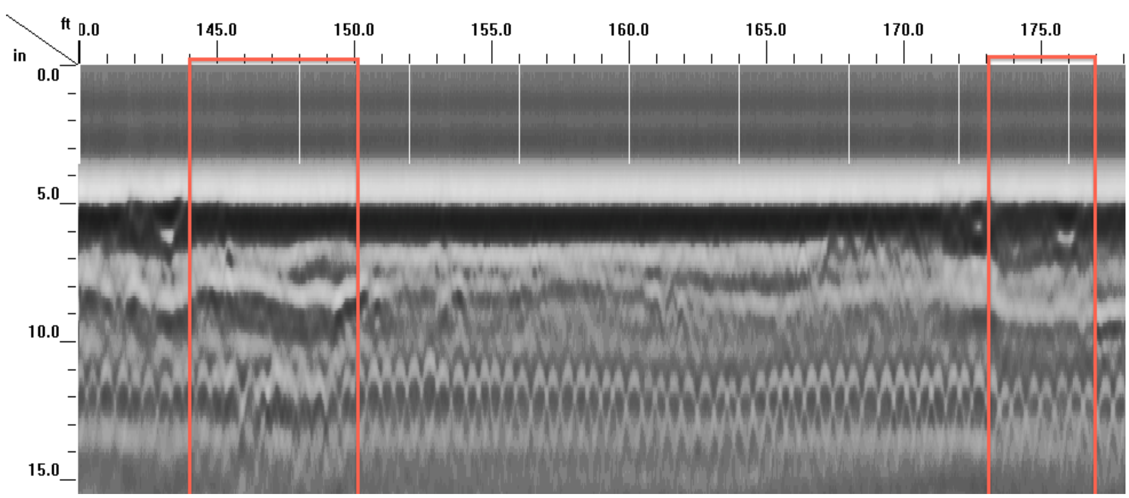


Figure 4-11 Pass number 2 of the GPR scans

The process of defining locations of signal attenuation was repeated for all of the 24 passes. The locations of the expected defects were carried out into AutoCAD and were drawn as lines. Each line corresponds to the start and the end of each area in which the signal was attenuated. For instance, the second pass will be highlighted from 0 to 1.83 m and from 8.84 to 10.06 m as shown in Figure 4-11. The AutoCAD results are presented in Figure 4-12.

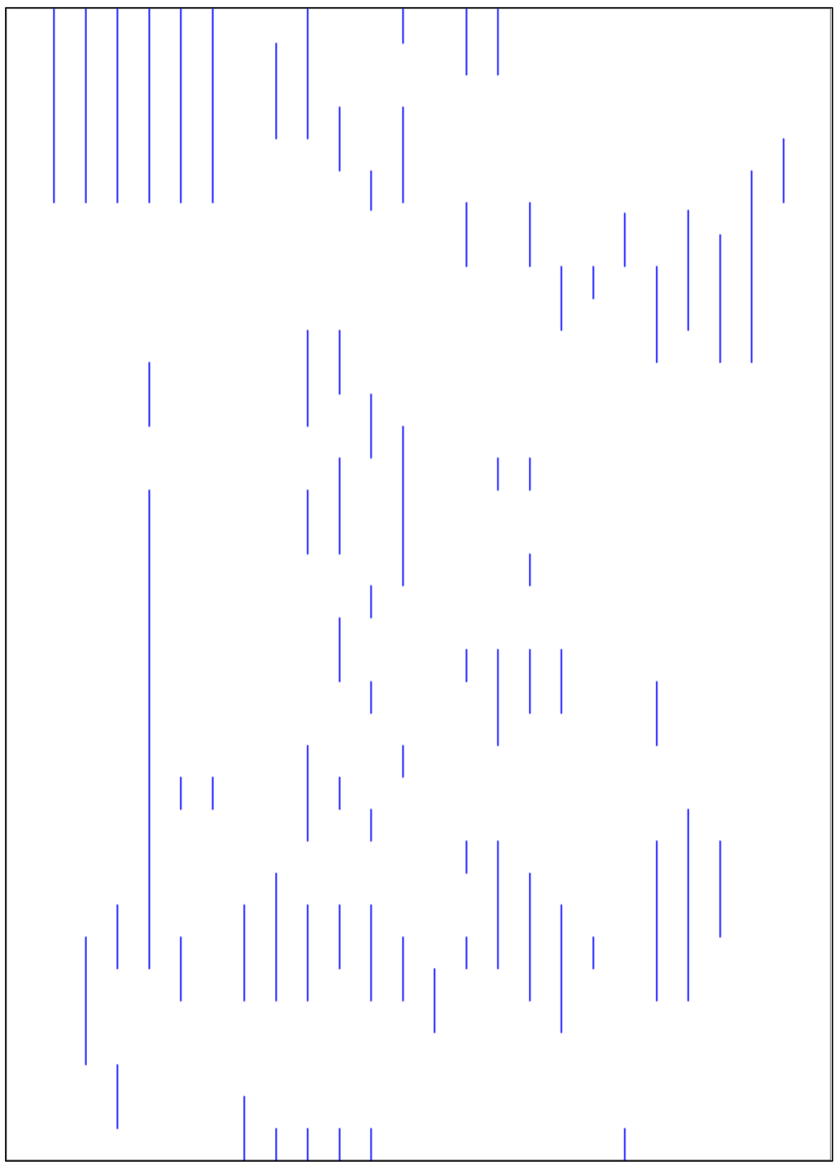


Figure 4-12 GPR results map

4.3.4 Hybrid System Results

The maps of the IR and GPR results are integrated (superimposed), and the resulting non-coinciding areas are removed. The final results are considered to identify detected defects. In addition, hammer sound test (which is one of the techniques used in current practice) was performed on the same area. The hammer sound test results are presented and used to validate the results of the proposed system. Finally, all inspection results are inputted into ArcGIS to generate visual representation of the detected defects in the form of maps.

Visual analysis for IR thermograph map and GPR profiles were done to locate potential areas of subsurface defects as described earlier. The integration was done as mentioned in Section 4.2.3. The maps of potential defects were drawn in AutoCAD. Figure 4-13-A shows the thermal IR map results. It shows the areas of high temperature or subsurface defects in red over the inspected part of the bridge after extracting the thermograph map from the background. Purple marks refer to surface defects detected by the IR camera. Figure 4-13-B shows the GPR results map. The locations of signal attenuations or potential defects located in each GPR profile are extracted in this figure. Figure 4-13-C is the map of the eliminated potential defects that were only detected by either one of the technologies. In other words, those areas represent the ones that do not coincide in IR and GPR maps and are not expected to be delaminated. Finally, Figure 4-13-D shows the coinciding potential defects that are detected by both IR and GPR.

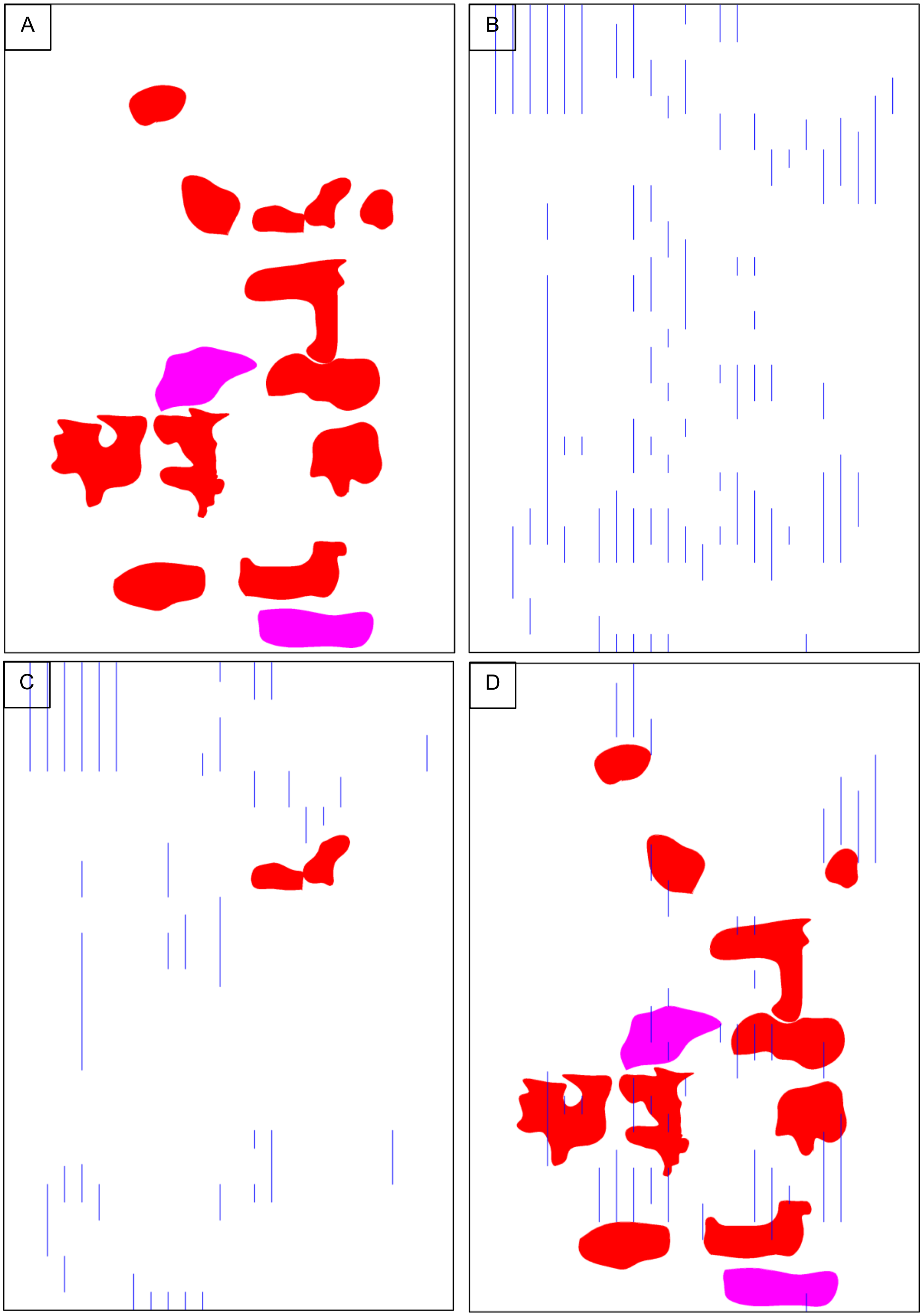


Figure 4-13 Maps of defects A) IR results, B) GPR results, C) Eliminated parts, and D) Hybrid system results

4.3.4.1 Visual Validation of The Results

The locations of defects generated by the hybrid system are shown in Figure 4-13-D, to visually verify the accuracy of the results another maps are generated including visual inspection results for surface defects in Figure 4-14 and hammer sound results for subsurface delamination in Figure 4-15 which are shown in green, those two maps act as the basis for visual verification as they represent the current practice. A good correlation can be observed as most of the areas are close to each other when compared with hummer sound test as shown in Figure 4-16. Further, most of the eliminated areas are different from the hammer sound test. Therefore, in a qualitative perspective, the results of the hybrid system represent almost the actual condition in terms of locations of detected defects.

In addition, results of the hybrid system are compared with results of the complete visual inspection as shown in Figure 4-17. The majority of the areas coincide, but visual inspection has detected additional areas not covered by the hybrid system. That is because of the different mechanisms at which the hybrid system (IR and GPR) and the visual inspection work. The hybrid system relies on temperature measurements and radar signals analysis, while visual inspection relies on visually assessing the condition by sight. In addition, the main focus of visual inspection is detecting surface defects while the hybrid system is mainly detecting subsurface defects.

Figure 4-14 Visual inspection results map

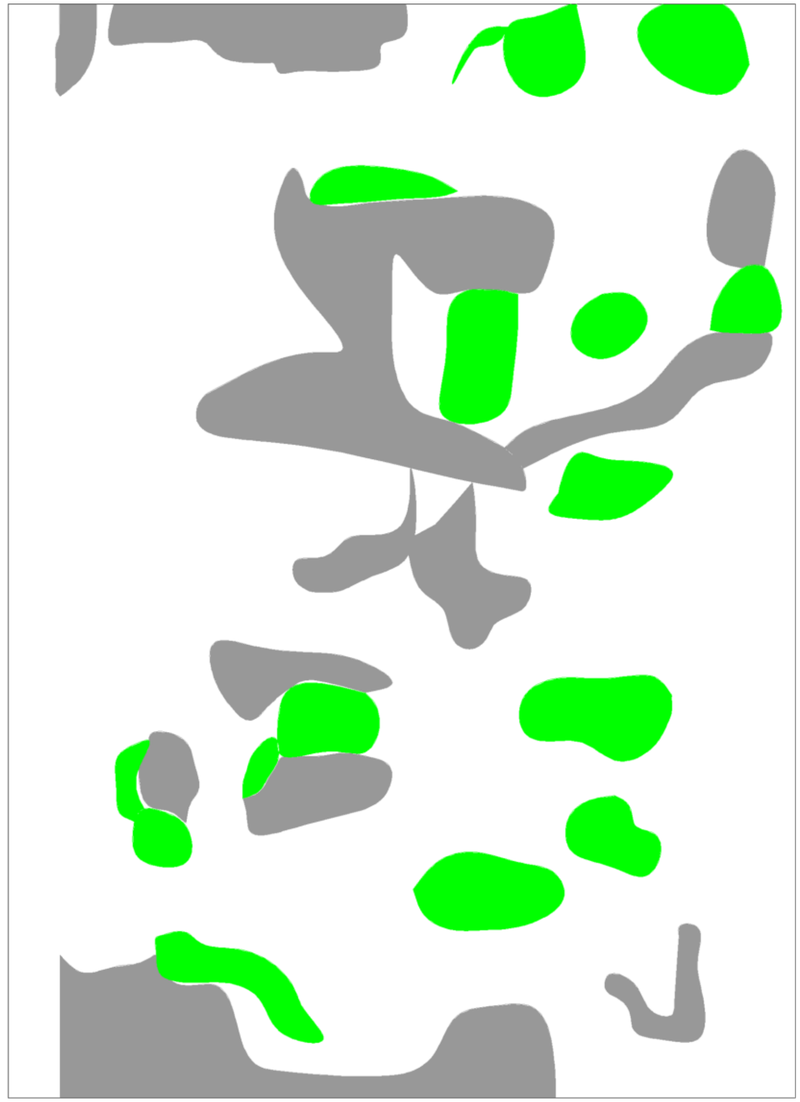


Figure 4-15 Visual inspection and hummer sound results map

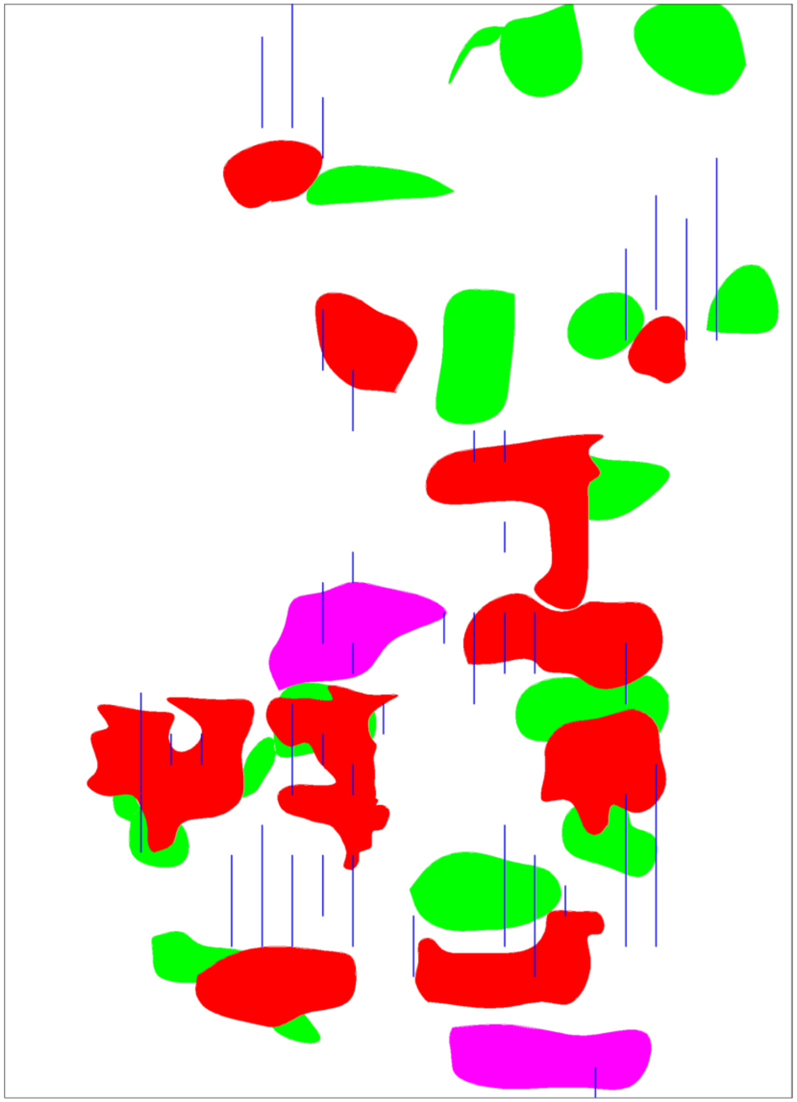


Figure 4-16 Hybrid system results with hummer sound test

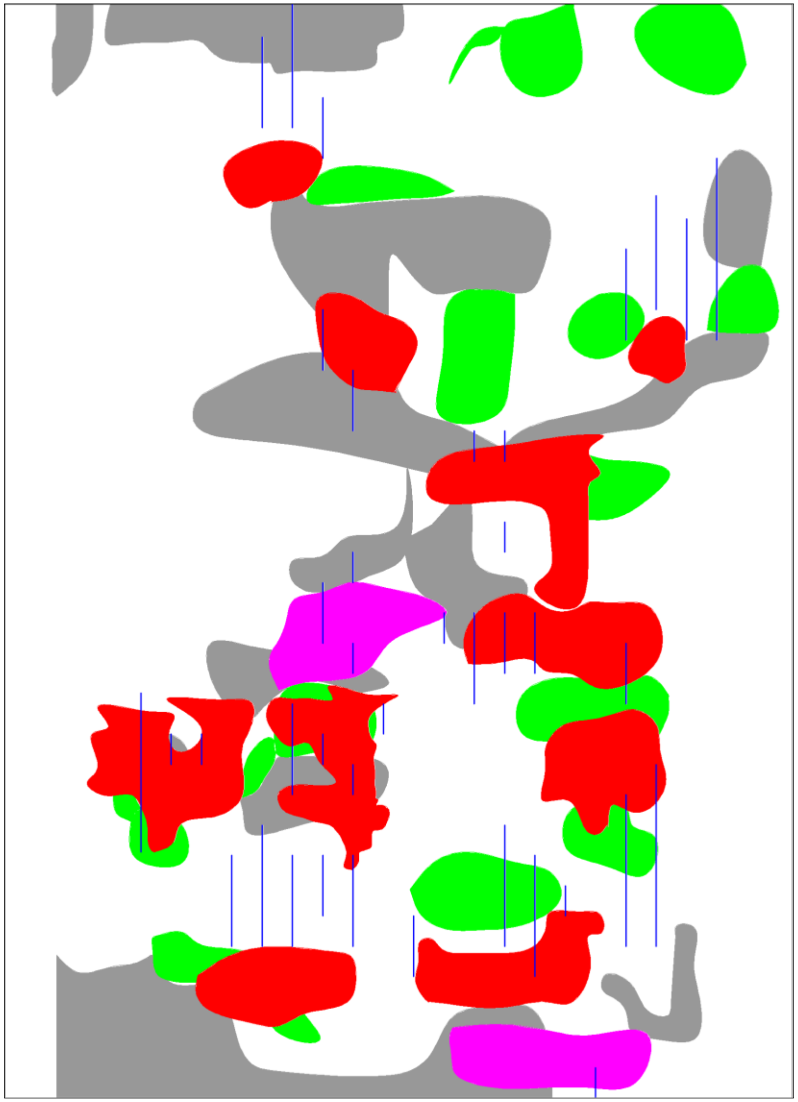


Figure 4-17 Hybrid system results with complete visual inspection

4.3.4.2 Numerical Validation of The Results

In a quantitative perspective, Table 4-2 summarizes the calculated areas of defects detected by each technology and shows the percentage of the area being defective compared to the whole area of the inspected bridge. Starting from the top of the table, IR map refers to the area of the defects detected in the thermograph map, shown in Figure 4-13-A. Reduced IR map refers to the area of defects after eliminating areas in the hybrid system, IR areas in Figure 4-16. IR subsurface represents the area of the defects detected by IR in red color only Figure 4-16. GPR refers to the total areas of defects detected in the GPR map, shown in Figure 4-13-B. As GPR results were presented earlier in linear units, they are clustered into areas that include group of those linear units by drawing best fit splines Figure 4-18-B. This is to calculate percentage error later and have consistent units. Reduced GPR refers to the total areas of defects detected by GPR after elimination, shown in Figure 4-18-B. Hammer sound refers to area of defects detected in the hammer sound, Figure 4-15 in green. Visual inspection refers to areas of surface defects in the visual inspection process, Figure 4-14.

The percentage difference between the IR subsurface and hammer sound is $\frac{IR-Hummer}{Average}\, x\, 100 = \frac{13.3-11.1}{12.2}\, x\, 100 = 18.1\%$. The percentage difference between GPR and hammer sound is $\frac{GPR-Hummer}{Average}\, x\, 100 = \frac{12.0-11.1}{10.17}\, x\, 100 = 7.8\%$. Therefore, the small percentage difference and the qualitative comparison between the results imply that the results of the hybrid system are in good correlation with the actual condition.

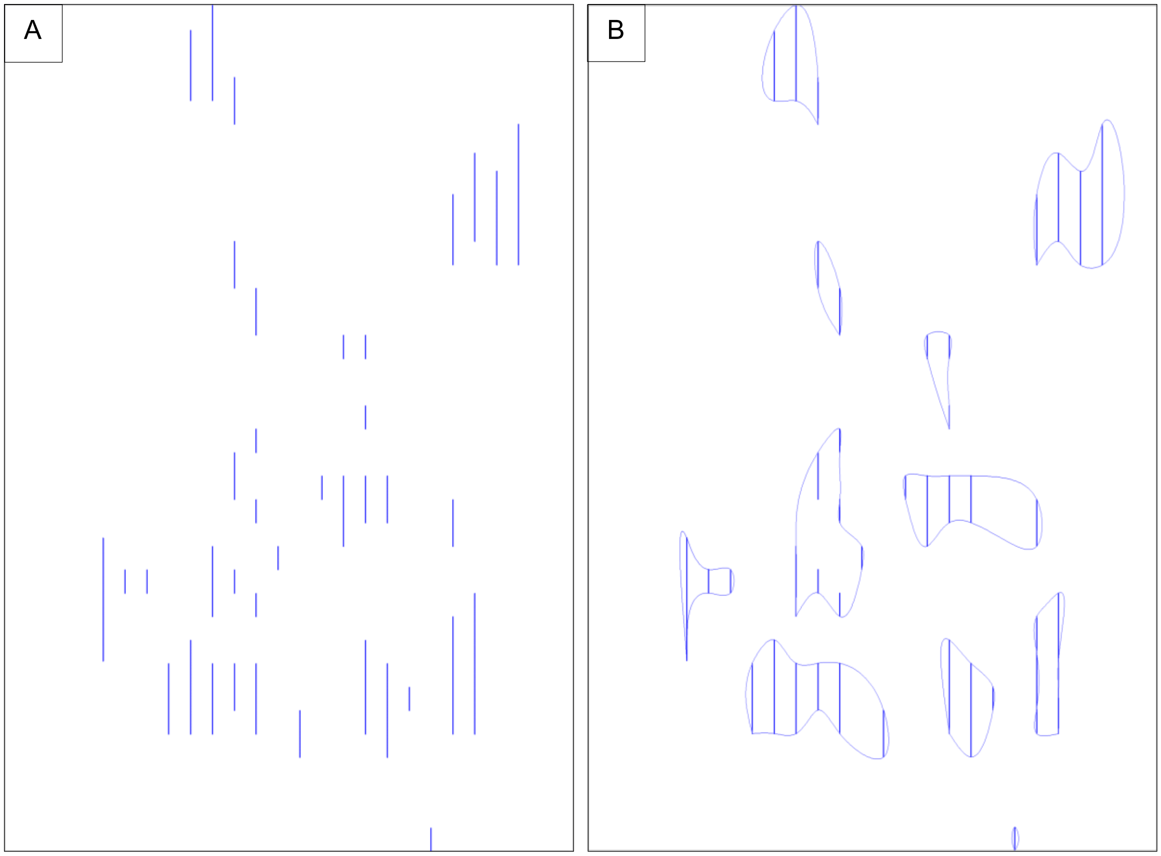


Figure 4-18 Best fit GPR areas A) GPR linear results B) GPR areas results with best fit splines

Table 4-2 Calculations of defective areas

Map	Full map area	Defective area	% Defected
IR map	77.11 m^2	13.22 m^2	17.1%
Reduced IR map	77.11 m^2	12.52 m^2	16.2%
IR subsurface	77.11 m^2	10.24 m^2	13.3%
GPR	77.11 m^2	19.32 m^2	25.1%
Reduced GPR	77.11 m^2	9.24 m^2	12.0%
Hammer Sound	77.11 m^2	8.54 m^2	11.1%
Visual Inspection	77.11 m^2	13.59 m^2	17.6%

4.3.4.3 Condition Rating

Condition rating of bridge cannot be achieved as only a 77m^2 segment was inspected. However, condition rating for the inspected section is calculated in Table 4-3 according to Minnesota Department of Transportation 2013 discussed in Section 4.2.3 and Table 4-1.

Table 4-3 Condition rating

Element	% Area defective	Condition rating
Thermal IR	16.2%	4
GPR	23.9%	4

Based on Table 4-3, the overall condition rating is 4, which corresponds to the second worst case a bridge can attain, as a condition state of 5 is the worst. Prior to the case study, the bridge was set for complete demolition based on previous reports and studies that indicated the bridge is in poor condition and is not useful for service. Two weeks after the case study, the demolition process started. That insures the validity of the results and the condition rate produced, as they represent partial condition rate of the bridge.

4.3.4.4 ArcGIS Visualization

Finally the results were inputted into ArcGIS. The inspected area was geo-referenced in ArcGIS by importing the coordinates of the boundaries of the area from Google Earth and using them as the boundaries of the maps in ArcGIS. Eight layers were used in ArcGIS. The first and the second layers are the base layers which represents the whole bridge and the inspected part of it. Figure 4-19 shows the two of the layers. The whole bridge map was imported from Google Earth. The second layer which is zoomed in the same figure represents the inspected part of the bridge at which the asphalt layer was removed. This is the map produced by combining all the regular images taken while performing the thermal IR test as discussed in 4.2.1. The rest of the layers will be presented on top of those layers.

The third, the fourth, and the fifth layers are the GPR results map, the IR results map, and the hammer sound test results map respectively. Those maps represent the results of the hybrid system along with the hammer sound test but they are separated into three different layers. The personnel can deselect any of the layers to focus on one or two if required. Figure 4-20 depicts the maps of the hybrid system, by selecting GPR and IR maps and deselect hammer sound test results. Figure 4-21 depicts the maps of the hybrid system over the map of the hammer sound test.

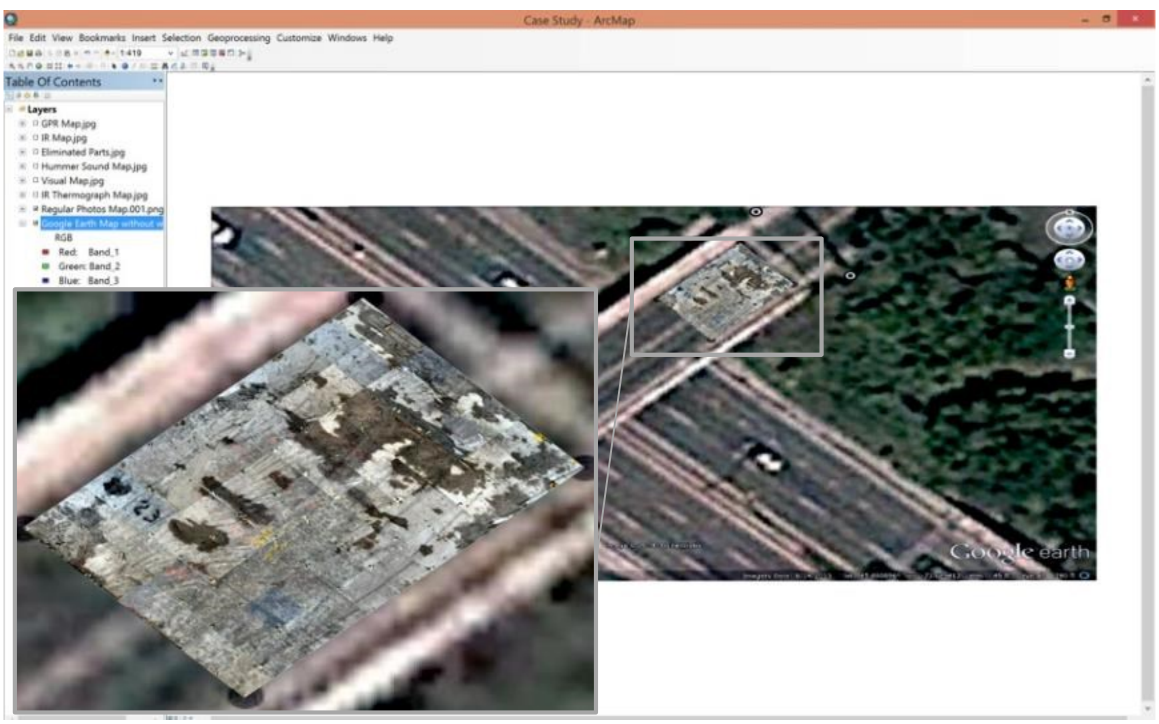


Figure 4-19 ArcGIS snapshot - bridge map

Figure 4-20 ArcGIS snapshot – hybrid system

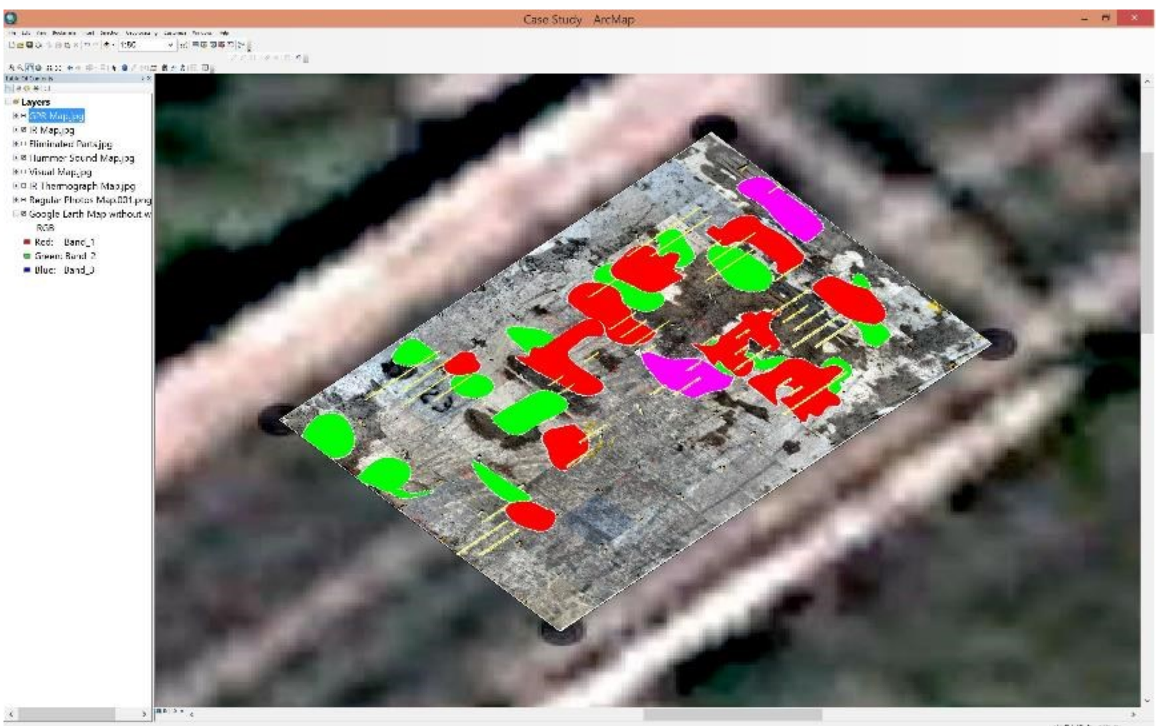


Figure 4-21 ArcGIS snapshot – hybrid system and hammer sound test

The sixth layer is the eliminated parts from the IR and GPR test. This layer is used as a reference if the personnel are planning to study the areas that have either one of high temperature or signal attenuation, depicted in Figure 4-22.

The seventh layer is called the visual map, Figure 4-23. This layer basically highlights the areas with extreme deterioration that have reached the surface of the concrete. Such areas have reinforcements exposed outside of the concrete to the atmosphere, or they represent unlevelled areas of concrete. This layer is added to incorporate the excessive surface defects in addition to the subsurface defects being detected by the hybrid system.

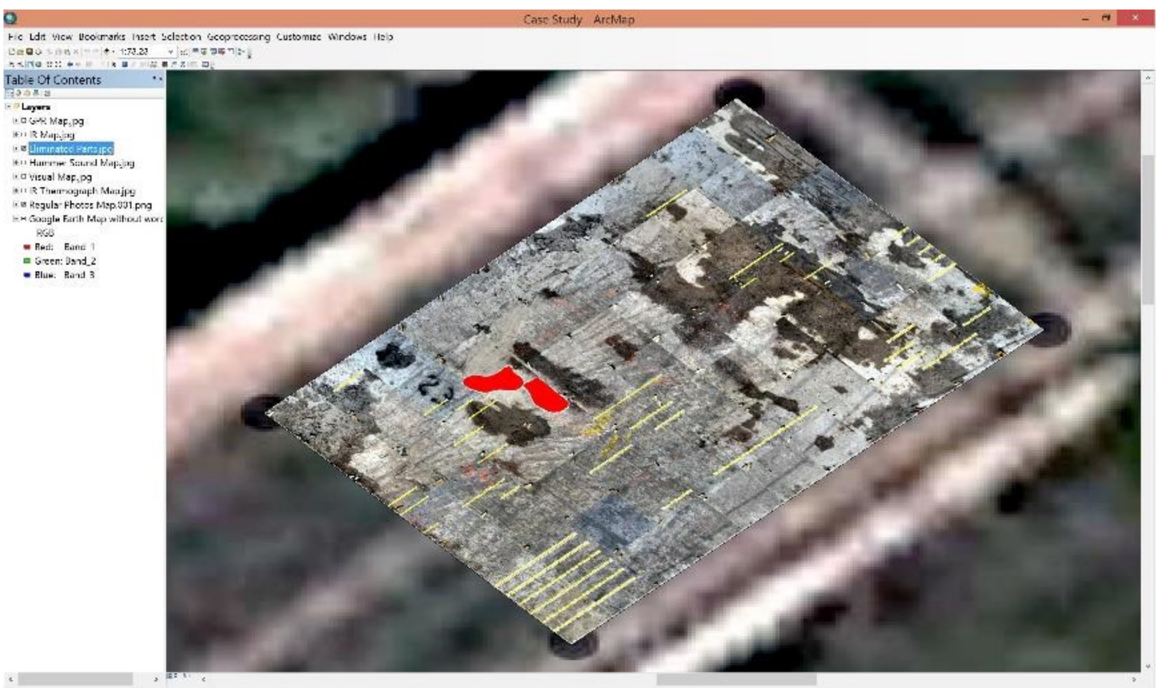


Figure 4-22 ArcGIS snapshot – eliminated parts

Figure 4-23 ArcGIS snapshot – surface defects

The eighth and the final map is the map that shows the IR thermograph map. Figure 4-24 depicts the thermograph map on top of the bridge map.

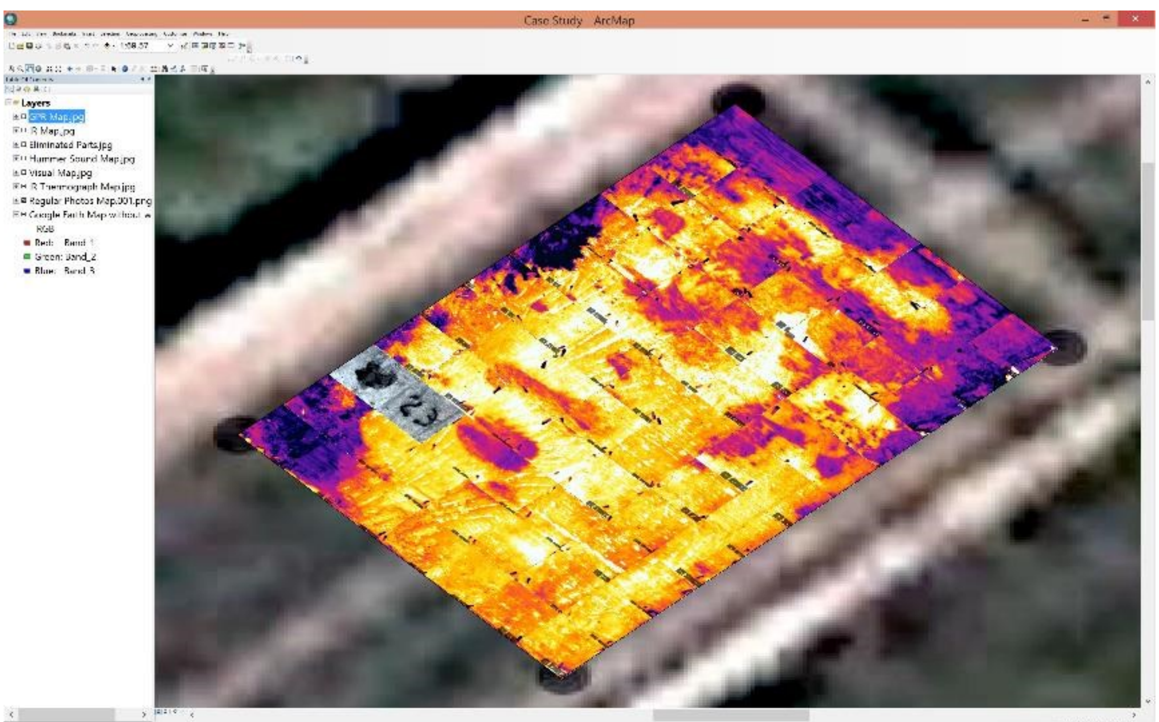


Figure 4-24 ArcGIS snapshot – thermograph map

4.3.5 Limitations of the Hybrid System

The proposed system has several limitations. Below are the main limitations of the proposed hybrid system.

- The system is limited to a specific two technologies based on available resources.
- The system is limited to concrete bridge inspection.
- The system was tested using only one case study.

CHAPTER 5 CONCLUSIONS, CONTRIBUTIONS, AND RECOMMENDATIONS

5.1 CONCLUSIONS

A methodology to augment the current practice in bridge inspection was developed. The methodology consist of three steps, defining the problem, developing a comparative study of remote sensing technologies, and finally developing a hybrid system of Thermal IR and GPR. The problem was defined when reviewing the current practice of bridge inspection worldwide and conducting the questionnaire. The main two limitations were the cause of traffic disruption and lane closure, and the lack of visualization of inspection reports. The proposed solution will be utilizing remote sensing technologies as they have the ability of acquiring data from a distance, thus minimizing traffic disruption. ArcGIS will be utilized to increase the visualization and understanding of the inspection data and the condition state.

The second step was to develop methodology to provide a systematic comparison among the different remote sensing technologies found in the literature. Seven technologies were studied. A model was developed. This model recommends the best remote sensing technology to be utilized based on project objectives and end-user preferences. One of the features of this model is that it is flexible. The flexibility of the model was ensured by studying a set of multi-attributed criteria where the end-user can add/remove and/or change weights of each criterion. The model utilizes Saaty's AHP in the comparison among the different technologies based on the criteria specified.

The final step is to recommend two technologies to be utilized. The two technologies will form a hybrid system. These technologies are Thermal IR and GPR. The selection of such technologies was based on available resources for the research. The results of the two technologies are combined to enhance the accuracy of each of them. Areas with high temperatures in the IR map will be defined. Locations of signal attenuation in every GPR profile will be defined as well. The two maps of the results will be added on top of each other. Areas that are not detected in both of the technologies will be eliminated. The final map will show areas of defects that are detected by both of the technologies. The proposed hybrid system was implemented in a case study in the city of Laval, Montreal, Quebec, Canada. Part of the bridge was inspected using the proposed method and using hammer sound test to verify the results. The results showed a good correlation. Finally, the maps of the defects were imported into ArcGIS for better representation of the defects and the condition of the bridge as a whole.

5.2 CONTRIBUTIONS

This research has made several contributions to the body of knowledge in the field of bridge condition assessment. Contributions are summarized as follows:

1. A comparative study of remote sensing technologies. This model is flexible and can be used to select the most suitable technologies to be utilized based on project conditions and end-user preferences.

2. The elopement of a hybrid system, which utilizes remote sensing technologies. This system has two unique advantages.

   i. Improve the accuracy of the results of Thermal IR and GPR; individually by integrating their results in an effort to eliminate areas of low possibility of being defective.

   ii. Improve the visualization of the inspection reports. Utilizing ArcGIS enhances the understanding of the conditions as defects are presented in maps of detected anomalies on top of the bridge map.

5.3 RECOMMENDATIONS

Based on the limitations and contributions of the research, several recommendations for future research can be summarized as follows:

1. The comparative study can be expanded to cover technologies that can be utilized on several structures and not limited to only concrete bridges.
2. The hybrid system proposed a methodology for implementation. The same methodology can be studied and be applied on different types of structures such as buildings or metro stations.
3. The proposed hybrid system can be integrated with other technologies such as DIC to detect surface defects on an image-basis. Data interpretation of the whole system can be enhanced by utilizing data fusion.

4. ArcGIS has abilities that are not covered in this research. It can be used to enhance the inspection reports. ArcGIS can further analyze the results presented. Algorithms can be used to calculate the defective areas. Notes can be added on each map. Reports can be generated from ArcGIS. And finally ArcGIS can share maps and results between several users for real time results. Reports can be viewed or updated on PCs, tablets, or smartphones.

REFERENCES

Adhikari, R. S., Moselhi, O., & Bagchi, A. (2013). A study of image-based element condition index for bridge inspection. *30th International Symposium on Automation and Robotics in Construction (ISARC 2013)*, Montréal, Canada. 345-356.

Adhikari, R., Moselhi, O., & Bagchi, A. (2012). Automated prediction of condition state rating in bridge inspection. *Gerontechnology, 11*(2), 81.

Ahlborn, T., Shuchman, R., Sutter, L., Brooks, C., Harris, D., Burns, J., . . . Oats, R. (2010). *An evaluation of commercially available remote sensors for assessing highway bridge condition.* Michigan Tech.

Ahlborn, T., Shuchman, R., Sutter, L., Harris, D., Brooks, C., & Burns, J. (2013). *Bridge condition assessment using remote sensors.* Michigan Technological University & Center for Automotive Research at Michigan Department of Transportation.

Ahlborn, T., Vaghefi, K., Harris, D., & Brooks, C. (2012). Measurement and communication of bridge performance with remote sensing technologies. *Transportation Research Record: Journal of the Transportation Research Board, 2292*(1), 141-149.

Al-Fares, R. (2005). The utility of synthetic aperture radar (SAR) interferometry in monitoring sinkhole subsidence: Subsidence of the devil's throat sinkhole area (Nevada, USA). *Sinkholes and the Engineering and Environmental Impacts of Karst (2005),* 541-547.

ASTM C876-91. (1999). *Standard test method for half-cell potentials of uncoated reinforcing steel in concrete.* American Society for Testing and Materials West Conshohocken.

ASTM D4788-03. (2003). *Standard test method for detecting delaminations in bridge decks using infrared thermography*. American Society for Testing and Materials.

ASTM D6087-08. (2008). *Standard test method for evaluating asphalt-covered concrete bridge decks using ground penetrating radar.* American Society for Testing and Materials.

Bevc, L., Mahut, B., & Grefstad, K. (1999). *Review of current practice for assessment of structural condition and classification of defects.* (No. 2).BRIME Project (Bridge Management in Europe), Deliverable D.

Bremner, T., Hover, K., Poston, R., Broomfield, J., Joseph, T., Price, R., . . . Clifton, J. (2001). *Protection of metals in concrete against corrosion (ACI 222).* American Concrete Institute.

Chen, S., Liu, W., Dai, K., Bian, H., & Hauser, E. (2011). Remote sensing for bridge monitoring. *Condition, Reliability, and Resilience Assessment of Tunnels and Bridges, 404*(16), 118-125.

Endsley, K. A., Brooks, C., Harris, D., Ahlborn, T., & Vaghefi, K. (2012). Decision support system for integrating remote sensing in bridge condition assessment and preservation. *SPIE Smart Structures and Materials Nondestructive Evaluation and Health Monitoring,* San Diego, California. *, 8345*

FHWA. (2004). *National bridge inspections standards regulation (NBIS) .* U.S. Department of Transportation.

FHWA. (2012). *Bridge inspector's reference manual.* U.S. Department of Transportation.

Gucunski, N., Imani, A., & Romer, F. (2013). *Nondestructive testing to identify concrete bridge deck deterioration* Transportation Research Board.

Hammad, A., Garrett, J. H., & Karimi, H. A. (2003). Mobile infrastructure management support system considering location and task awareness. : *Towards a Vision for Information Technology in Civil Engineering,* 1-10.

Hellier, C. (2001). *Handbook of nondestructive evaluation* McGraw-Hill New York.

Hing, C. C., & Halabe, U. B. (2010). Nondestructive testing of GFRP bridge decks using ground penetrating radar and infrared thermography. *Journal of Bridge Engineering, 15*(SPECIAL ISSUE: Bridge Inspection and Evaluation), 391-398.

Hong, Q., Wallace, R., Dennis, E., & Forster, M. (2012). *Economic evaluation of commercial remote sensors for bridge health monitoring.* Center for Automotive Research & Transportation Systems Analysis Group.

Jiang, S. F., & Zhang, C. (2009). Design and implementation of a WEBGIS-based quality evaluation system for bridge construction. *The 1st International Conference on Information Science and Engineering (ICISE2009),* 4257-4261.

Johnson, C. R., & Goldman, M. J. (1990). GIS: Easing infrastructure management. *Civil Engineering - ASCE, 60*(6), 42-44.

Kharkovsky, S., Case, J., Ghasr, M., Zoughi, R., Bae, S., & Belarbi, A. (2011). Application of microwave 3D SAR imaging technique for evaluation of corrosion in steel rebars embedded in cement-based structures. *Review of Progress in Quantitative Nondestructive Evaluation: Volume 31,* Burlington, VT. *, 1430*(1) 1516-1523.

Laefer, D. F., Fitzgerald, M., Maloney, E. M., Coyne, D., Lennon, D., & Morrish, S. W. (2009). Lateral image degradation in terrestrial laser scanning. *Structural Engineering International, 19*(2), 184-189.

Lin, J. M., & Sansalone, M. (1996). Impact-echo studies of interfacial bond quality in concrete: Part I-effects of unbonded fraction of area. *ACI Materials Journal, 93*(3)

Liu, W. (2010). *Terrestrial LiDAR-based bridge evaluation.* PhD Thesis, University of North Carolina at Charlotte). *71*(06)

Ministry of Transportation, Ontario. (2000). *Ontario structures inspection manual.* Ontario, Canada: Ontario Ministry of transportation.

Minnesota Department of Transportation. (2013). *Bridge inspection field manual*. MnDOT Bridge Office.

Moropoulou, A., Avdelidis, N., Koui, M., Aggelopoulos, A., & Karmis, P. (2002). Infrared thermography and ground penetrating radar for airport pavements assessment. *Nondestructive Testing and Evaluation, 18*(1), 37-42.

Moufti, S. (2013). *A defect-based approach for detailed condition assessment of concrete bridges.* Master's Thesis at Concordia University).

National Bridge Inventory (NBI). (2012). *Deficient bridges by state and highway system 2011.* U.S. Department of Transportation.

Ontario Structure Inspection Manual. (2008). *Inspection form - 22-1002/.* Ontario Structure Inspection Manual.

Ormsby, T. (2009). *Getting to know ArcGIS desktop: Basics of ArcView, ArcEditor, and ArcInfo* (2, update for ArcGIS 93 ed.). Redlands, Calif.: ESRI Press.

Queensland Department of Main Road. (2004). *Bridge inspection manual.* (No. 80.640). Queensland, Australia: Department of Main Roads, Transport Technology Division.

Rhazi, J. (2009). Half-cell potential test from the upper-side and the lower-side of reinforced cconcrete slabs: A comparative study. *NDTCE'09, Non-Destructive Testing in Civil Engineering,* Nantes, France.

Saaty, T. L. (1994). *Fundamentals of decision making and priority theory with the analytic hierarchy process*. Pittsburgh, PA, USA: RWS Publications.

Sabins, F. (1986). *Remote sensing: Principles and interpretation.* (No. 124).New York, Oxford: W. H. Freeman & Co.

Shinozuka, M., & Loh, K. (2004). Remote sensing with the synthetic aperture radar (SAR) for urban damage detection. *Engineering, Construction, and Operations in Challenging Environments,* 223-230.

Shroff, A. C. (2008). Remote sensing techniques for bridge deck evaluation. *2008 Concrete Bridge Conference,* St. Louis MO.

Tarussov, A., Vandry, M., & De La Haza, A. (2013). Condition assessment of concrete structures using a new analysis method: Ground-penetrating radar computer-assisted visual interpretation. *Construction and Building Materials, 38*, 1246-1254.

The Department of Bridge Inspection & Maintenance, Alberta. (2008). *Bridge inspection and maintenance system - inspection manual.* Government of the Province of Alberta.

Transport Canada. (2012). *Transportation in canada 2011 – comprehensive review. .* Ottawa, ON, Canada: Minister of Public Works and Government Services.

Transportation Research Board. (2007). *NCHRP synthesis 375: Bridge inspection practices.* Washington, DC: NCHRP: National Cooperative Highway Research Program.

Vaghefi, K., Ahlborn, T., Harris, D., & Brooks, C. (2013). Combined imaging technologies for concrete bridge deck condition assessment. *Journal of Performance of Constructed Facilities,*

Vaghefi, K., Oats, R., Harris, D., Ahlborn, T., Brooks, C., Endsley, K. A., . . . Dobson, R. (2012). Evaluation of commercially available remote sensors for highway bridge condition assessment. *Journal of Bridge Engineering, 17*(6), 886-895.

Vaghefi, K., Silva, H., Harris, D., & Ahlborn, T. (2011). Application of thermal IR imagery for concrete bridge inspection. *Precast/Prestressed Concrete Institute Convention and National Bridge Conference,* Salt Lake City, Utah.

Washer, G. (2003). Nondestructive evaluation of highway bridges in the United States. *The International Symposium on Non-Destructive Testing in Civil Engineering,* Berlin, Germany.

Washer, G., Bolleni, N., & Fenwick, R. (2010). Thermographic imaging of subsurface deterioration in concrete bridges. *Transportation Research Record: Journal of the Transportation Research Board, 2201*(1), 27-33.

Wisconsin Department of Transportation. (2011*). Wisconsin structure inspection manual*. Wisconsin, USA:

Wu, X., Yao, H., Xie, D., & Xu, Z. (2012). Developing of management information system of road and bridge infrastructure based on ArcGIS engine. *Remote Sensing, Environment and Transportation Engineering (RSETE), 2012 2nd International Conference on,* (IEEE), 1-3.

Yaghi, S., Abu Dabous, S., Alkass, S., & Moselhi, O. (2014). A comparative study of remote sensing technologies for bridge condition assessment. *CSCE 2014 General Conference - Congrès Général 2014 De La SCGC*, Halifax, NS.

APPENDIX A: Questionnaire

BRIDGE CONDITION ASSESSMENT: CURRENT PRACTICE QUESTIONNAIRE

This questionnaire is designed to be integrated in a master's thesis research. It is divided into two parts; part 1 (bridge inspection) with 11 questions, and part 2 (bridge deterioration modeling) with 2 questions. It will take 8-10 minutes to finish the questions. The information provided will be confidential and strictly for research purpose only. Finally, if you prefer us sharing the findings of this questionnaire with you; please cross the check box at the end of this page with Email address. In completing the questions please cross check the boxes with the appropriate answer and provide comments in the space below.

Objectives:

- Update the current practice in bridge inspection.
- Capturing bridge deterioration modeling in current pra8ctice

Respondent Information	
Name	
Position	
Company	
Years of Experience	
Area of Expertise	
Date	

Would you like us to share the findings of this questionnaire with you?

- ❑ Yes ❑ No

If yes, Email address:

Statistics:

1. Do you keep a database for bridge inventory?

❑ Yes ❑ No

If yes, how many bridges are there?

Breakdown of the bridges:

______ Concrete bridges ______ Steel bridges

Other types:

What is the average age of the bridges?

______ years

What is the average rating of the bridges inventory?

______

Bridge inspection:

1. What Bridge Management System do you use?

❑ Ontario Bridge Management System ❑ PONTIS

❑ BRIDGIT ❑ None

❑ Other, please specify:

2. Is Non-Destructive testing (NDT) used only upon the recommendation of the bridge inspector?

❑ Yes ❑ No

If no, when?

3. What NDT do you use?

❑ Ultrasonic Pulse Echo ❑ Half-Cell Potential

❑ Ultrasonic Surface Waves ❑ Electrical Resistivity

❑ Impulse Response ❑ Chain and hammer

❑ Impact Echo ❑ None

4. Do you use Ground Penetrating Radar (GPR)?

❑ Yes ❑ No

If yes, for what purposes?

5. How often do you perform lane closure?

❑ Every inspection ❑ At detailed inspection (once every two years)

❑ Other

6. Do you identify locations of defects?

❑ Yes ❑ No

If yes, do you keep record of the defects details?

❑ Yes ❑ No

7. What is the computational platform of data storage and data analysis? (example: MS excel, MATLAB,…, none)

Data Storage:

Data Analysis:

8. What condition rating system do you use?

❑ Descriptive; “excellent, very good, …, poor” ❑ Numeric; “9, …, 1”

❑ Indices; “0-100; 0-1” ❑ Other

9. Does the condition rating reflect the condition of the whole bridge?

❑ Yes, the entire bridge ❑ Only elements of the bridge

❑ Only components and elements of the bridge

10. How do you produce the overall condition rating of an element?

- ❑ By assessing the whole element
- ❑ By assessing only the visible parts
- ❑ By assessing critical parts, or as mentioned in previous reports
- ❑ Other

11. In few words, what is the procedure followed to produce condition ratings for the components, and for the whole bridge?
