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Evaluation of Bridge Decks Using Non-Destructive Evaluation (NDE) at Near Highway Speeds for Effective Asset Management

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16. Abstract

Remote sensing technologies allow for the condition evaluation of bridge decks at near highway speed. Data collection at near highway speed for assessment of the top of the concrete deck and proof of concept testing for the underside of the deck was conducted for surface and subsurface evaluation. 3-D photogrammetry was combined with passive thermography to detect spalls, cracks and delaminations for the top of the concrete bridge deck, while active thermography was investigated for bottom deck surface condition assessment. Successful field demonstrations validated results comparable to MDOT inspections. Recommendations for immediate implementation for condition assessment of the top of a concrete deck are included for introducing the BridgeViewer Remote Camera System into current bridge inspections to provide a photo inventory of the bridge deck captured at 45mph and above using GoPro cameras. The combined optical photogrammetry (3DOBS) and passive thermography technologies provide an objective analysis of spalls, cracks and suspected delaminations while traveling at near highways speed. Using the same 3DOBS technology with higher resolution cameras and slower speeds, cracks can be detected as small as 1/32 in. Laboratory and field demonstrations show active thermography would benefit from further development as a remote sensing technology for condition assessment on the underside of the bridge deck.

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Executive Summary

Just over 30% of the U.S. transportation infrastructure has passed its expected service life soon (FHWA 2011). The rate at which we build new bridges has subsided in the past decades as the nation has changed to a focus on preservation of the infrastructure. Enhanced inspection techniques for bridge condition assessment are directly related to this focus as effective assessment management is founded on quality objective bridge inspection techniques.

Development of commercially available and rapidly advancing technologies has lead to a renewed interest in remote sensing. Remote sensing applications for bridge inspection means the ability to evaluate the condition of a bridge in a hands-off manner without traffic disruption. Such applications can increase public mobility and safety of inspectors, as well as reduce inspection times and improve subjective inspection methods and reporting. Enhanced inspections lead to effective asset management through improved data for decision support and prioritization of preservation projects.

From a maintenance and preservation perspective, the bridge deck is the critical component in protecting the remaining superstructure and substructure from the environment and contaminants while taking on a primary role for load transfer. As a result, one of the first elements besides bridge deck joints of a bridge to deteriorate and consequently require attention is the deck. Therefore, thorough assessment of the condition of this component is necessary to ensure the integrity of the bridge structure. To accurately assess the condition of this major component, it is equally important to evaluate both the top and bottom of the deck. Only after thorough evaluation of both can the integrity and remaining service life of the bridge be determined.

This research project investigated non-destructive evaluation (NDE) techniques deployable at- or near-highway speed augmenting bridge deck inspection programs, by detecting and quantifying delaminations, cracks and spalls, for the top surface of the concrete bridge deck. In addition, the condition of the concrete deck bottom surface was evaluated in a hands-off manner using remote sensing technologies including 3-D photogrammetry and active thermography. Outreach activities included training sessions for MDOT personnel to understand and implement these technologies.

Condition Assessment of the Top Surface of Concrete Bridge Decks

Health indicators for distress in concrete bridge decks include spalls, cracking and delaminations. The top surface of the deck is typically visually inspected while subsurface degradation is often determined by sounding with hammer or with a chain drag. Principals of photogrammetry and thermography, both non-destructive remote sensing technologies, were demonstrated as tools for condition assessment of health indicators.

Passive thermal imaging and a 3-D Optical Bridge-evaluation System (3DOBS, an application of 3-D photogrammetry) were combined for detecting spalls and delaminations on the top deck surface at near-highway speeds. Passive thermography is a more mature technology used to locate suspected delaminations and is capable of operating at highway speed. The 3DOBS system, previously used at walking speed, was upgraded to a camera system with a high frame rate for implementation at near highway speed to detect spalls. Using a higher resolution 3DOBS system at slower speeds, crack size and location detection was demonstrated on cracks as small as 1/32 in. In addition, the Bridge Viewer Remote Camera System (BVRCS), also an optical system using Go-Pro cameras, was developed to provide a high-resolution photo inventory of the top deck surface while travelling at highway speed.

Two field deployments of the non-destructive testing methods were conducted. Emphasis during the first deployment was on the evaluation of individual technologies including the 3DOBS high-resolution system to detect spalls and cracking, and evaluation of the passive infrared thermography to detect delaminations. The results of the first deployment were used as a basis for comparison for the second deployment. The remote sensing techniques were evaluated, systems upgraded, vehicular mounting system improved, and lab testing was conducted between deployment phases.

Figure ES-1: Deployment without traffic disruption

The second deployment allowed for further evaluation of the 3DOBS low-resolution system and passive infrared thermography conducted simultaneously at near highway speeds, demonstrating the data collection process without traffic disruption (see Figure 1). This deployment also allowed for implementation and evaluation of the 3DOBS high-resolution system at slower speeds for more refined crack evaluation. For comparison purposes, an MDOT certified bridge inspector was present for the Maryland Ave field tests to establish ground-truth information. Results from the remote sensing tests were evaluated based on the inspector's findings.

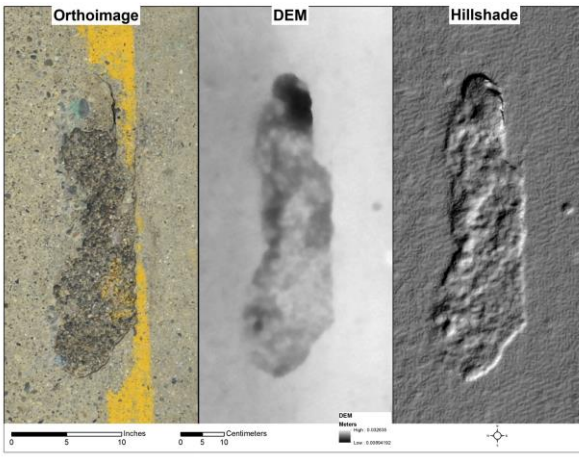

Figure ES-2: Generated data layers

Eight layers of georeferenced datasets from the collected imagery is available for decision support. The layers include an

orthoimage, digital elevation model (DEM), hillshade of DEM, LAS point cloud of the bridge deck, thermal mosaic, detected spalls, detected cracks, and potential delaminations. A combination of these layers could enable MDOT to perform a change detection analysis on the distresses and provide objective data to assist in generating condition states assessments and NBI ratings for the top surface of the concrete bridge deck.

The BridgeViewer Remote Camera System (BVRCS) was developed and successfully demonstrated for documenting the top surface of the bridge deck with a high resolution geo-tagged photo inventory using GoPro cameras at operating speeds of 45 mph and above. By incorporating BVRCS into bridge deck assessments, MDOT can quickly obtain temporally accurate imagery of bridge decks and store the information into photo inventories. These inventories can be accessed for use prior to the next inspection or during preliminary bridge scoping.

Condition Assessment of the Bottom Surface of Concrete Bridge Decks

The condition of the bottom surface of the deck is subjected to the same types of distress as the top surfaces including subsurface spalls and cracks, and delaminations. However, access can be limited and techniques applicable for condition of the top surface may not be effective for assessment of the bottom surface. Active thermography involves an external heat source rather than the sun to impart heat on the system. 3DOBS photogrammetry was used in conjunction with the active thermal IR testing method to evaluate the bottom surface of the deck. Laboratory tests focused on reducing inspection time and the portability of equipment. The results validated the method for a proof of concept field demonstration.

Field testing was performed to evaluate the bottom surface of the deck using active thermal IR. Weather conditions during the field demonstration dictated that a pier cap be evaluated rather than a fascia beam in addition to the bottom deck surface.

Results indicate that this remote sensing technology is acceptable for detecting and quantifying delaminations. A simple polygon method for analysis was developed to quantify delamination areas for comparison to MDOT ground truth. In all cases, the current MDOT hammer sounding method of inspection for estimating the area of delamination was conservative relative to active thermography results.

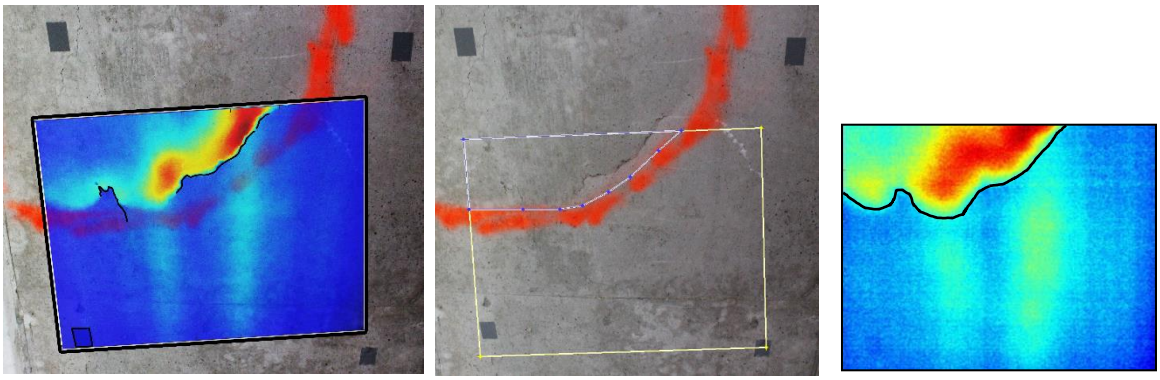

Figure ES-3: Results of active thermography testing on the underside of a concrete bridge deck

As with technologies deployed for the top deck surface evaluation, implementation of this remote sensing technology can best be realized through further development prior to implementation. Improvements in data analysis, repeatability of the test method and results, and reduced testing time are parameters that need to be further addressed.

Outreach Activities

With an objective of gaining an understanding of the field readiness and demand for technologies by current bridge inspectors, a general training session was conducted to provide a hands-on equipment demonstration of the 3DOBS, BVRCS and active IR thermography systems. The presentation slides are presented in an appendix. Outcomes included the request for an additional training session specific to the data processing for the 3DOBS photogrammetry imagery, which was provided. Attendees, including inspectors, region bridge engineers and photogrammetry experts, agreed that BVRCS was ready for deployment and requested an additional training session and a “How To” manual for use (Appendix H). The combined technologies of 3DOBS and passive thermography for top of deck condition assessment are near ready for implementation and will require additional pilot studies prior to full implementation. Bottom of deck assessment techniques were recommended for further study.

1. Introduction

As the nation's concrete highway bridges age, bridge inspectors and engineers demand easily deployable condition assessment technologies. Effective asset management facilitated by a comprehensive evaluation method for bridge decks and structures is not only a priority for transportation departments, but also a major factor in determining the priority of bridge preservation activities. While these evaluation methods provide engineers with valuable information regarding the remaining service life of structures and whether maintenance should be performed, it is important that inspections and assessments be conducted consistently and accurately to inform good decisions.

Non-destructive evaluation (NDE) techniques have been long sought after to provide complete and accurate assessment of bridge condition. Remote sensing, a subset of NDE, can be of even more benefit to the bridge inspection and management community by providing an avenue for collection of bridge health data, without direct contact, leading to little or no traffic disruption (Ahlborn et al. 2012). Therefore, to the bridge industry, the term *remote sensing* can be used interchangeably with NDE when NDE does not come into contact with the element being inspected. To the bridge inspector, remote sensing provides an opportunity to assess the condition of the bridge without traffic disruption.

Numerous indicators of bridge condition can be assessed using remote sensing technologies. For example, concrete delamination is one of the indicators of steel reinforcement deterioration within concrete bridge elements. Quantifying the area of delamination can result in a more accurate estimate of the deck deficiency allowing for a more suitable National Bridge Inventory (NBI) rating. Significant deficient area (>10%) on the bottom side of the bridge deck results in a poor condition rating of the bridge deck. In the case of excessive delaminated areas on the bottom side of the concrete deck, false decking is installed over the travel lane to prevent damage to the traffic underneath the bridge (MDOT 2008), and in many cases bridge decks will be scheduled for replacement instead of rehabilitation practices.

Routine bridge inspection usually involves visual inspection of bridge elements and taking notes of deficient areas. In the case of excessive indicators of deterioration, an in-depth inspection is scheduled. In general, an in-depth bridge inspection for the underside of a bridge deck includes the use of conventional inspection practices such as hammer sounding, which is labor intensive, subjective, and often requires traffic lane closures resulting in mobility concerns such as transit disruptions and safety concerns for inspectors. Delaminated areas reveal hollow sounds when tapped with a hammer compared to a sharp tone of intact concrete allowing inspectors to locate and quantify defective areas.

It is recognized that no single technology can assess the complete condition of a highway bridge. While some technologies remain in their infancy for use in bridge inspections, many such as optical, thermal, and ground penetrating radar, have had some success in determining the condition of concrete bridge elements. Combining remote sensing technologies with

current common practices has been found to be beneficial to detecting surface and subsurface indicators for specific bridge elements (Vaghefi et. al, 2012).

Using remote sensing technologies at highway speed can eliminate the need for lane closures, reduce mobility costs and improve safety. But little research has been conducted at highway speed. In fact, most studies have considered static testing or testing at walking speed. The current study presented herein combines three technologies (thermal, photographic and photogrammetric) by evaluating their performance at various speeds, including near-highway speed, to assess bridge deck health indicators.

1.1 Objectives

This research was conducted to:

1. Investigate non-destructive evaluation (NDE) techniques that can be deployed at- or near-highway speed augmenting bridge deck inspection programs, by detecting and quantifying delaminations, cracks and spalls, for the top surface of the concrete bridge deck.
2. Investigate the condition of the concrete deck bottom surfaces and fascia beams in a hands-off manner using remote sensing technologies.
3. Provide MDOT employees with training to deploy acceptable technologies.

1.2 Scope

To accomplish the objectives, the research team took a multifaceted approach dividing the effort among several tasks. Because the technologies are changing and improving quickly in today's market, a comprehensive literature review centered on what is being done commercially and academically in the area of remote sensing for bridge condition assessment. The review includes a general assessment of common types of deterioration of concrete bridge decks, as well as the current MDOT methods of practice and an overview of NDE assessment methods including the current state of remote sensing technologies for assessing the condition of concrete bridge decks and fascia elements.

Individual technologies, specifically thermal and optical imaging, were considered for further evaluation. Upgrading equipment and data fusion of these technologies for a combined assessment was first performed in the laboratory environment before conducting field demonstrations at near highway speed. Primary tasks were divided into two groups considering the top surface of the bridge deck with testing at near highway speed, and the bottom surface and fascia beams.

Passive thermal imaging and a 3-D Optical Bridge-evaluation System (3DOBS, an application of 3-D photogrammetry) were combined for detecting spalls and delaminations on the top deck surface at near-highway speeds. Passive thermography is a more mature technology used to

locate suspected delaminations and is capable of operating at highway speed. The 3DOBS system, previously used at walking speed, was implemented at near-highway speed to detect spalls using a lower resolution camera system. Using a higher resolution system and slower speeds, crack size and location was investigated. In addition, the Bridge Viewer Remote Camera System (BVRCS), also an optical system using Go-Pro cameras, was enhanced to provide a high-resolution photo inventory of the top deck surface while travelling at highway speed.

Assessing the condition of the bottom surface of the deck was more challenging and was not intended to operate in transit. Rather, active thermography (using an external heat source) was investigated in the laboratory prior to the proof-of-concept field demonstration to detect subsurface delaminations. Combining active thermography with 3DOBS allowed for data to be overlaid such that cracking and delaminations could be assessed in a combined fashion.

Educating a workforce of bridge inspectors was an integral part of this research project. Training, including equipment demonstration, was provided for MDOT personnel showing all remote-sensing technologies investigated. Further training was specifically developed for bridge inspectors to implement BVRCS. Additional training was provided to assist MDOT personnel in understanding data fusion and processing such that MDOT can begin implementation.

Combining technologies results in a bridge inspection suite of tools that represents a highly integrated, multi-spectral, and multi-sensor inspection system that provides an assessment of several health indicators for surface and subsurface issues. The vetting of these technologies, individually and combined, through laboratory studies and field demonstrations are described herein, along with conclusions and recommendations for implementation.

2. Literature Review

2.1 Review of Previous Research

The maintenance, preservation, and improvement of transportation infrastructure is a growing challenge for state and local governments, particularly for bridges. Billions of dollars are needed to repair and replace aging bridges, with one recent estimate at $140 billion (AASHTO 2008). Following the I-35W bridge collapse in August 2007, the deteriorating condition of bridges has been under increased scrutiny by government officials, as well as the public. This emphasis is warranted considering that approximately 25 percent of the nation's 600,000 bridges are either structurally deficient or functionally obsolete. In Michigan, 12 percent of the state's 11,000 bridges are structurally deficient. This statistic highlights the need for upgrading and replacing existing infrastructure, and underscores the importance of quality inspection and assessment mechanisms to prioritize these efforts.

Many methods have been applied to the inspection of bridge deck systems, including coring of the pavement, conductivity tests, and pavement sounding using acoustical devices and ground penetrating radar (GPR). These techniques are generally time consuming, labor intensive, tedious, operator dependent and cost prohibitive. Furthermore, traffic control dilemmas caused by current bridge deck inspection techniques increase safety and mobility concerns for both inspection teams and the traveling public alike.

The primary components of a bridge can be categorized as the bridge deck, superstructure and substructure. The superstructure is responsible for supporting the bridge deck by means of beams and the substructure transfers loads from the superstructure to the ground through abutments and piers. While all three components are essential to the performance of a bridge, the bridge deck is of major interest due to the primary role of transferring loads to the superstructure and substructure and determines when preservation activities are to be performed to a specific structure. From a maintenance and condition evaluation perspective, bridge decks serve as the driving surface while also providing protection from the environmental and contaminant impacts (e.g., salts and chemicals) to the superstructure and substructure elements below. As a result, the first element of a bridge to deteriorate and consequently require attention is frequently the deck. Therefore, thorough assessment of the condition of this component is necessary to ensure the integrity of the bridge structure. To accurately assess the condition of this major component, it is equally important to evaluate both the top and bottom of the deck. Only after thorough evaluation of both can the integrity and remaining service life of the bridge be determined.

During routine bridge inspections, decks are evaluated visually and if an in-depth inspection is needed, a more detailed study is conducted. Sounding by hammer or by chain dragging are MDOT's current methods for conducting a delamination study and are only as effective as the

person who is conducting or reading the tests. Because the separated layers inside concrete can cause an interruption in sound wave transmission through the concrete, sounding methods are the most common techniques for detecting delaminated areas. Tapping concrete with a metal rod or a light weight hammer on concrete bridge elements and dragging a chain across the concrete bridge deck are the most common methods for detecting delaminations during a bridge inspection. Delaminated areas reveal hollow sounds when tapped with a hammer compared to a sharp tone of intact concrete and this can indicate the defective area. The chain drag method involves dragging a heavy chain across the bridge deck and marking the hollow sounding area with spray paint similar to the hammer sounding technique (Ryan et al. 2006; Jana 2007).

Both assessment techniques are labor intensive, require traffic control over the bridge deck and are dependent on the inspector's training and experience. These bridge deck evaluations determine the presence of not only delaminations, but also cracking, spalling, scaling, and even fascia and expansion joint conditions throughout the structure.

Evaluation of bridge deck cracking is also a labor intensive. During detailed scoping inspections when lanes are closed, inspectors evaluate the entire bridge deck for cracking. This involves the inspector walking down each lane, drawing cracking patterns, measuring crack widths and estimating length and location on the deck. Crack widths are measured using a crack gauge which has to be held up the crack for accurate measurements. Smaller hairline cracking can be missed during the inspection due to lighting conditions or the ability of the inspector to see small cracks.

No less important is the condition of the deck bottom surface. While the bridge deck riding surface is the most prominent topic of discussion in bridge condition assessment, problems with the bottom surface and fascia can be disastrous and possibly fatal. Ascertaining their condition periodically is extremely important when considering the possibility of bridge debris falling on passing traffic. Current underside in-depth inspection techniques are limited to hammer-soundings. This method provides both access challenges and safety concerns to inspectors working over traffic lanes. In addition, such inspections are time consuming and subject to an individual inspectors training and experience.

A combination of thermal imaging and electro-optical technologies allows inspectors to assess surface and subsurface health indicators in a less subjective manner. These new inspection methods will improve consistency among inspectors and provide more accurate quantitative results. With the potential of these sensors being mounted to vehicles, these technologies offer DOTs the ability to collect data while driving across bridges. The purpose of this report is to provide background on bridge health indicators and overview of application of thermal and electro-optical imagery to assess health indicators of the bridge deck, fascia beams and underside. This is done by evaluating prior research on these technologies including the findings from the recent USDOT/RITA project "Bridge Condition Assessment Using Remote Sensors" (www.mtri.org/bridgecondition).

2.1.1 Common types of deterioration of concrete bridge decks

Within the state of Michigan, 79% of total bridge deck systems are either concrete cast- in-place or precast concrete panels (FHWA 2011). Therefore, evaluation of the concrete bridge decks is the main focus of this report. A bridge deck can be classified, to a certain extent, as a sacrificial element because it can be replaced as it degrades. However, as the integrity of the deck is compromised during the degradation process, the protection afforded to the superstructure and substructure elements also diminishes, often providing a catalyst for deterioration or accelerating degradation of these elements.

In general, assessing the condition of a bridge deck includes detecting deck health indicators such as spalls, scaling, map cracking and delaminations as well as monitoring the vertical and horizontal cracks on the bridge deck and expansion joints condition. These health indicators are classified as surface and subsurface measures that-indicate the condition of both the top and bottom surfaces of the deck as well as the deck fascia.

Current practice for detecting bridge deck health indicators during bridge inspections includes visual inspection, chain dragging the bridge deck top surface and hammer sounding the bridge deck top, bottom and fascia. Not all bridges undergo an in-depth inspection using chain dragging and hammer sounding techniques. The severity of the bridge deck condition is identified through visual inspections and financial demands related to traffic control are considered before in-depth inspections are performed.

2.1.2 Bridge health indicators

Table 2-1 shows bridge health indicators used to assign condition for concrete bridge deck and fascia based on the guidelines provided by MDOT for the National Bridge Inventory (NBI) rating (MDOT 2011) and AASHTO for Pontis condition state rating (AASHTO 2011). Methods that are listed in this table are the tools generally being used by transportation agencies to conduct an in-depth inspection survey and rate bridges in NBI scheme. However, in more critical cases and where a NDE tool is available, an in-depth inspection with a NDE tool may be conducted to provide additional information regarding the deck deficiency.

Table 2-1: Bridge Health Indicators for Concrete Bridges

Location		***Bridge Health Indicator***	***Required Measurements***	***Current practice methods***
Deck Top	Surface	Spalls, scaling	1/4" depth * 6" diameter **	Visual inspection
		Cracking	1/32" wide *	Visual inspection
		Map cracking	spacing of 1ft **	Visual inspection
	Subsurface	Delamination	6" diameter **	Chain drag, Hammer sound
Deck Bottom	Surface	Spalls, scaling	1/4" depth * 6" diameter **	Visual inspection
		Cracking	1/32" wide *	Visual inspection
		Map cracking	spacing of 1ft **	Visual inspection
	Subsurface	Delamination	6" diameter **	Hammer sound
Fascia (prestressed concrete beam)	Surface	Spalls, scaling	1/4" depth * 6" diameter **	Visual inspection
		Cracking	0.004" wide **	Visual inspection
		Map cracking	spacing of 1ft **	Visual inspection
	Subsurface	Delamination	6" diameter **	Hammer sound

* reference: MDOT 2011
** reference: AASHTO 2011

2.1.2.1 Delaminations

Delaminations are separations of concrete layers generally over and near the top layer of rebar. Delaminations can express themselves as horizontal cracked planes in concrete slabs that at times deflect vertically to represent on the deck surface. As these cracked planes are so small

in size and virtually undetectable to the human eye, determining the exact location and area of delamination during visual bridge inspections involves numerous challenges and difficulties. Corrosion of reinforcing steel in concrete bridges has been highlighted as the main cause of delamination in literature (FHWA 2006; Jana 2007). Freeze-thaw cycles and overstress in a member are other factors that can also cause delaminations. Delaminated areas can completely separate from the concrete bridge elements and develop into spalls; thus, it is important to identify the location and size of these areas accurately.

2.1.2.2 Map Cracking

Map cracking is the distress of concrete decks in which the surface has a pattern of cracks caused by material failure. Traditional inspection techniques used for the assessment of map cracking include visual evaluation, ultrasonic testing, and impact- echo (FHWA 2006). According to the *AASHTO Manual for Bridge Element Inspection*, cracking on the bridge can be assessed based on the crack width and density, and then classified into four different condition states for repair decision-making process, see Figure 2-1. Detecting areas of map cracking is critical for bridge deck condition assessment as these areas can indicate a delaminated area or rebar corrosion underneath. Map cracking at the bottom surface of the deck can be more critical due to the safety issue for underneath traffic. Also, identifying areas of cracking allows for preventative maintenance actions to prevent further chloride ingress and corrosion inside concrete.

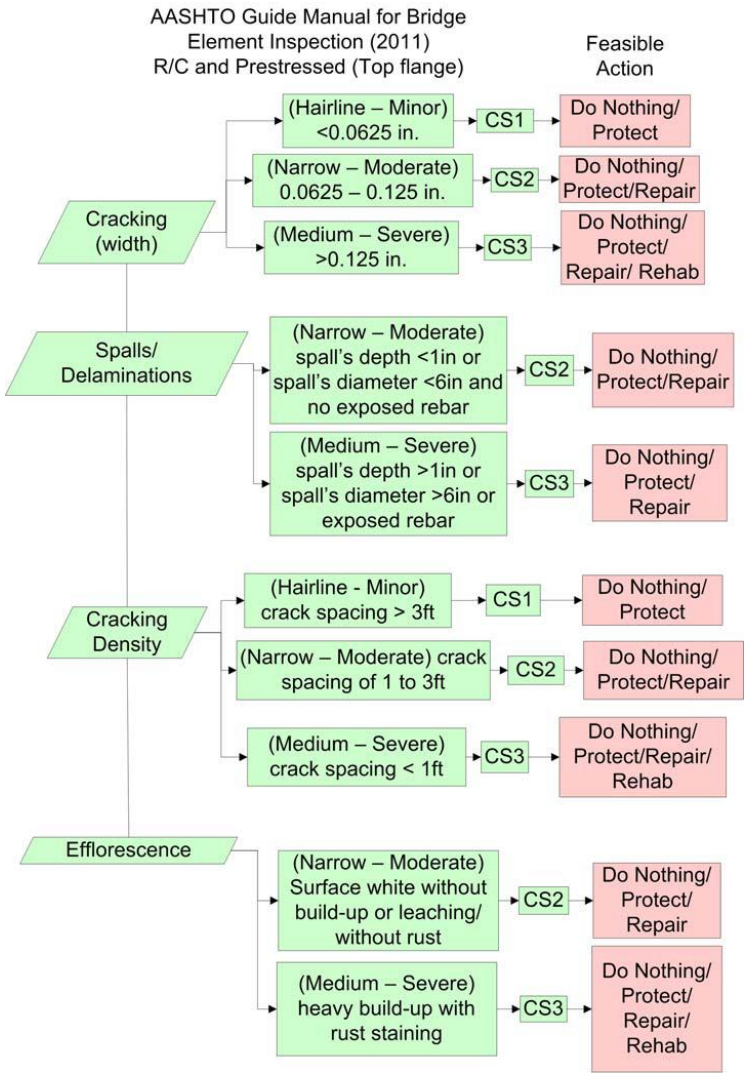

Figure 2-1: Summary of the AASHTO Repair Guideline for Concrete Bridge Decks and Top Flange of Prestressed Concrete Bridges.

2.1.2.3 Spalling and Scaling

Spalling and scaling on the bridge top and bottom surfaces of the deck are defined as the loss of material due to corrosion of rebar or distress on the concrete deck surface. For the purpose of this document and research, spalling is considered on the order of magnitude of 1/4 to 1 inch in depth (FHWA 2006; MDOT 2011) and 6 inches in diameter (AASHTO 2011). The current method for identifying the amount of spalling on a bridge structure is visual assessment. Detecting spalls is necessary over the bridge deck, specifically on the wheel path and riding surfaces. Also, spalls and scaling on the top or bottom surface of the bridge deck can indicate the presence of subsurface defects such as a large area of delamination and can be significantly important for bridge deck condition assessment and the decision to proceed with preservation activities.

2.1.2.4 Deck Fascia Condition

According to the MDOT Bridge Element Inspection Manual, condition of the bridge deck fascia can be assessed and classified into four different condition states based on the amount of spalling and cracking on the fascia, possibility of large spalls dropping of the bridge, and strength of the railing (MDOT 2007). The current methods of deck fascia inspection are primarily visual and hammer sounding, with the use of crack width gauge where accessible and needed.

Detecting delaminated areas on the bridge deck fascia is more critical to determining the condition of this structural component than identifying cracks. Delaminated areas on the fascia can turn into spalls and can raise safety issues for traffic passing underneath the bridge.

2.1.2.5 Expansion Joint Condition

There are several different types of distress related to the expansion joints of a bridge that are also common indicators of overall bridge health. These include torn or missing seals, armored plate damage, chemical leaching on joint bottoms, cracks within two feet of the joint and spalls within two feet of the joint. The magnitude threshold of cracking and spalling is identical to those for surface cracking (1/16 to 3/16 inch in width) and spalling (1/4 to 1 inch in depth) (FHWA 2006).

2.1.3 Current MDOT practice methods for bridge condition assessment

Bridge inspection information is recorded in the bridge safety inspection report, the *Michigan Bridge Element Inspection Report*, and in the detailed scoping documents. The *MDOT Bridge Deck Preservation Matrix and Project Scoping Manual* provides various maintenance activity decision guidelines and an associated fixed life for each activity (MDOT 2009; MDOT 2011).

During biennial bridge inspections, both top and bottom surface of the bridge deck are inspected and total percent deck deficiency is included in the bridge safety inspection reports. Also, qualitative assessment of the deteriorating conditions, such as location and significance of the spalls, cracks or delaminations, is explained for each bridge element. Michigan Bridge Deck Preservation Matrix provides guidance for bridge deck condition decision (Table 2-2). Referring to this matrix, deficiency percent is defined as total percent of deck surface area that is spalled, delaminated or patched with temporary patch materials. This matrix was created from element deterioration data, and the intellect of individuals from Construction and Technology, Maintenance and Design Support Areas, and FHWA. The guidelines established by this matrix lead to an economical repair decision, which can be Capital Scheduled Maintenance (CSM), Capital Preventive Maintenance (CPM), Rehabilitation or Replacement (MDOT 2008). Current bridge inspection practices usually involve visual

inspection of the bridge elements and quantification of crack widths and spall dimensions. Inspections are conducted over accessible areas on the bridge as traffic allows.

Table 2-2: Bridge Deck Preservation Matrix

BRIDGE DECK PRESERVATION MATRIX – Decks with Uncoated "Black" Rebar

DECK CONDITION STATE				REPAIR OPTIONS	POTENTIAL RESULT TO DECK BSIR		ANTICIPATED FIX LIFE
Top Surface		Bottom Surface			Top Surface BSIR #58a	Bottom Surface BSIR #58b	
BSIR #58a	Deficiencies % (a)	BSIR #58b	Deficiencies % (b)				
≥ 5	N/A	N/A	N/A	Hold (c) Seal Cracks/Healer Sealer (d)	No Change	No Change	1 to 4 years
	≤ 5%	> 5	≤ 2%	Epoxy Overlay	8, 9	No Change	10 to 15 years
	≤ 10%	≥ 4	≤ 25%	Deck Patch (e)	Up by 1 pt.	No Change	3 to 10 years
4 or 5	10% to 25%	5 or 6	≤ 10%	Deep Concrete Overlay (h)	8, 9	No Change	25 to 30 years
		4	10% to 25%	Shallow Concrete Overlay (h, i)	8, 9	No Change	20 to 25 years
				HMA Overlay with water-proofing membrane (f, h, i)	8, 9	No Change	8 to 10 years
		2 or 3	> 25%	HMA Cap (g, h, i)	8, 9	No Change	2 to 4 years
≤ 3	>25%	> 5	< 2%	Deep Concrete Overlay (h)	8, 9	No Change	20 to 25 years
		4 or 5	2% to 25%	Shallow Concrete Overlay (h, i)	8, 9	No Change	10 years
				HMA Overlay with water-proofing membrane (f, h, i)	8, 9	No Change	5 to 7 years
		2 or 3	>25%	HMA Cap (g, h, i)	8, 9	No Change	1 to 3 years
				Replacement with Epoxy Coated Rebar (ECR) Deck	9	9	60+ years

(a) Percent of deck surface area that is spalled, delaminated, or patched with temporary patch material.
(b) Percent of deck underside area that is spalled, delaminated or map cracked.
(c) The "Hold" option implies that there is on-going maintenance of filling potholes with cold patch and scaling of incipient spalls.
(d) Seal cracks when cracks are easily visible and minimal map cracking. Apply healer sealer when crack density is too great to seal individually by hand. Sustains the current condition longer.
(e) Crack sealing can also be used to seal the perimeter of deck patches.
(f) Hot Mix Asphalt overlay with waterproofing membrane. Deck patching required prior to placement of waterproofing membrane.
(g) Hot Mix Asphalt cap without waterproofing membrane for ride quality improvement. Deck should be scheduled for replacement in the 5 year plan.
(h) If bridge crosses over traveled lanes and the deck contains slag aggregate, do deck replacement.
(i) When deck bottom surface is rated poor (or worse) and may have loose or delaminated concrete over traveled lanes, an in-depth inspection should be scheduled. Any loose or delaminated concrete should be scaled off and false decking should be placed over traveled lanes where there is potential for additional concrete to become loose.

Bridge Deck Preservation Matrix **June 8, 2011 Rev.**

Biennial routine inspection is the most common method of bridge inspection practices. During a routine bridge inspection, a bridge inspector visually observes the bridge and makes notes of deficient areas. These notes along with general measurements of the bridge are included in Bridge Safety Inspection Report (BSIR). Because this type of inspection relies on assessing the bridge visually, there are some limitations for evaluating areas that are not sufficiently visible or that raise safety issues for inspectors. Although routine bridge inspection focuses on overall condition of all the bridge components, the main attention is mostly on the deficient areas that were found in previous inspections and were indicated in the inspection report (Fu 2005). In-depth inspections, which include chain dragging, hammer sounding or the use of other NDE methods, are more comprehensive than biennial inspections, require lane closure over or under the bridge and are conducted more regularly on poor condition bridges. However, these types of inspections are not a required practice during a biennial inspection and are only completed when additional condition information is required and preservation activities become a priority. Chain dragging and hammer sounding along with the more commercialized version of an electro-mechanical sounding cart are standardized in ASTM D4580 – *Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding*. The main components of an electro mechanical cart include a battery, two tapping wheels, two sonic receivers and a strip recorder (ASTM 1997). This device can detect delaminations up to 2.6 inches below the surface (Jana 2007).

An investigation of the reliability of routine and in-depth visual inspection for highway bridges (Moore et al. 2000), reported significant variability in deck delamination surveys conducted by 22 bridge inspection teams. Basic hammer and chain dragging were the only tools used in this survey and the range of delamination percentage results varied from 2 to 35%. Studies such as this highlight the inconsistency current techniques due to differences in training and experience and reveal the need for an easy to use inspection tool to help bridge inspectors locate and sketch delaminations more accurately and objectively.

2.1.4 Overview of NDE assessment methods

Previous evaluations of NDE methods demonstrate the potential of these techniques to detect deteriorations, provide more accurate assessments, and reduce inspection time of concrete bridge decks (Vaghefi et al. 2012). These methods include: Ground Penetrating Radar, infrared thermography, LiDAR, aerial photogrammetry, UAV photogrammetry, impact echo, visual inspection, chain drag and hammer sounding. Previous studies related to bridge condition assessment have established that there is no single technology available that can provide sufficient information for both surface and subsurface bridge deck defects (Ahlborn et al. 2012; Gucunski et al. 2013). Therefore, the focus of this study is the combination of two NDE technologies for comprehensive detection and quantification of bridge deck deterioration. Infrared thermography and electro-optical imagery showed the great promise for practical use at near-highway speed, based on Ahlborn's previous USDOT-RITA study. Infrared thermography improves the accuracy of quantifying subsurface defects and electro-optical

imagery enhances visual inspection significantly by reducing inspection times, ability to collect subjective and repeatable measurements and provide high resolution datasets for evaluation.

2.1.4.1 Infrared Thermography

Infrared thermography is a technology based on collecting the radiant surface temperature and converting that temperature measurement into a visual image. Thermal infrared radiant energy is emitted from all objects that have a temperature greater than absolute zero. The radiant temperature (T_{rad}) of an object is defined by the amount of electromagnetic energy exiting the object in the range of two electromagnetic spectrum windows: 3-5μm and 8-14μm. This value is slightly lower than the true kinetic temperature (T_{kin}) of any object due to the fact that objects are not perfect emitters (Jenson 2007).

An object that radiates the absorbed energy at a maximum possible rate is called a blackbody. This theoretical construct helps to define the amount of heat that can be radiated from an object. According to the Stefan-Boltzmann law, the amount of radiant energy exiting a blackbody is proportional to the fourth power of its temperature and expressed as:

$$M_b = \sigma {T_{rad}}^4 \qquad \text{Equation 2-1}$$

where, M_b is the total emitted radiation of a blackbody which is equal to the kinetic temperature; T_{rad} is the radiant temperature and σ is the Stefan-Boltzmann constant (5.6697×10^{-8} $Wm^{-2}k^{-4}$). However, for real objects the amount of radiated energy is lower than the amount of absorbed energy. Therefore, the radiant temperature of the real object is lower than the true kinetic temperature. Emissivity of the material is the factor that affects the radiant temperature measurement of the material surface and defines the correlation between the true kinetic temperature and the radiant temperature of an object. This correlation defines with the equation below.

$$\varepsilon = \left(\frac{T_{rad}}{T_{kin}}\right)^4 \qquad \text{Equation 2-2}$$

Radiant flux is defined as the amount of electromagnetic energy exiting an object. Emissivity depends on the amount of radiant flux emitted from a material and has the value between 0 and 1. This value is almost equal to 1 for a blackbody; therefore, the radiant temperature for a blackbody is almost equal to the true kinetic temperature.

The value for emissivity of concrete is typically considered to be greater than 0.9 for concrete. Characteristics such as surface roughness, color, moisture content, viewing angle and field of view are some of the factors that can influence the emissivity of objects (Jenson 2007). Objects with darker colors absorb and emit more energy than lighter colored objects due

to the higher emissivity of darker colored objects. Surface roughness can influence the amount of radiant energy absorbed and emitted from an object, therefore, it influences the emissivity and radiant temperature of an object. Objects with higher moisture content have higher emissivity, thus absorb and emit more electromagnetic energy. Also, the emissivity can change based on the viewing angle; this mostly affects the measurements under the bridge and between the bridge girders. A smaller field of view results in a higher spatial resolution compared to a larger field of view; it will be different to look at a 2ft by 2ft concrete surface compared to looking at the whole bridge in one image.

A thermal IR camera is a tool for collecting the radiant surface temperature data of an object and generating a thermal IR image. Each pixel on a thermal infrared image is designated with a temperature data. Commonly, a range of minimum to maximum temperature on each image is shown as a sidebar on the image and assigned with false color values to create a visual image. Radiation, conduction and convection are three methods of heat transfer that can affect the heat flow through concrete. Although radiated energy is the parameter that can be measured by a thermal IR camera, the heat conductivity within the concrete and heat convection around the concrete can also influence this measurement.

The estimated emissivity value of 0.95 for concrete can be considered for collecting thermal IR images with the purpose of detecting subsurface abnormalities and defects as the actual temperature values are not of interest in this data collection. The emissivity value is inserted as an input on the thermal IR camera software while collecting data to achieve temperature results close to the true kinetic temperature. In measuring the defective areas in concrete, the temperature difference between sound concrete and defective area is in the interest of the inspector. Materials with reflective surface, such as duct tape, have lower emissivity compared to concrete; therefore, it will appear with lower temperature on the thermal infrared image.

Two approaches considered in conducting an infrared thermography test include passive and active. In the literature mostly related to the non-destructive testing (NDT) field, passive infrared thermography is generally defined as a method to detect the flaws in materials without using an external heater. In the passive method, an object radiates heat due to its internal heating system or properties. Inspecting the insulation of building envelops, heating floors and gas leaks are some of the applications of passive infrared thermography. On the other hand, active infrared thermography is described as a method to collect thermal infrared images after heating the object with an external heating system. In this method, the radiated heat is different from the defective and sound areas. Therefore, defective areas are revealed on the thermal infrared image (Maldague 1993; Starnes 2002). Recording the time is crucial in active infrared thermography to allow for resolving the depth and size of the flaw and obtain quantitative information.

The concept behind the application of passive infrared thermography in concrete bridge evaluation is that the anomalies and subsurface delaminations interrupt the heat transfer through the concrete and appear with different temperatures on the thermal IR image compared to the

area of surrounding sound concrete. During the day, as the ambient temperature increases, concrete absorbs heat and starts emitting radiant energy.

Delaminations and air voids within the concrete-resist the heat transfer and warm up at a faster rate than surrounding sound concrete, thus they appear as hot areas on the thermal IR image if captured during the day. However, during the night, as the ambient temperature decreases, sound concrete around delaminations lose heat at a lower rate compared to the defected area, thus the delaminations appear as cold areas on the thermal IR images (Washer et al. 2009 a). This concept is illustrated in Figure 2-2.

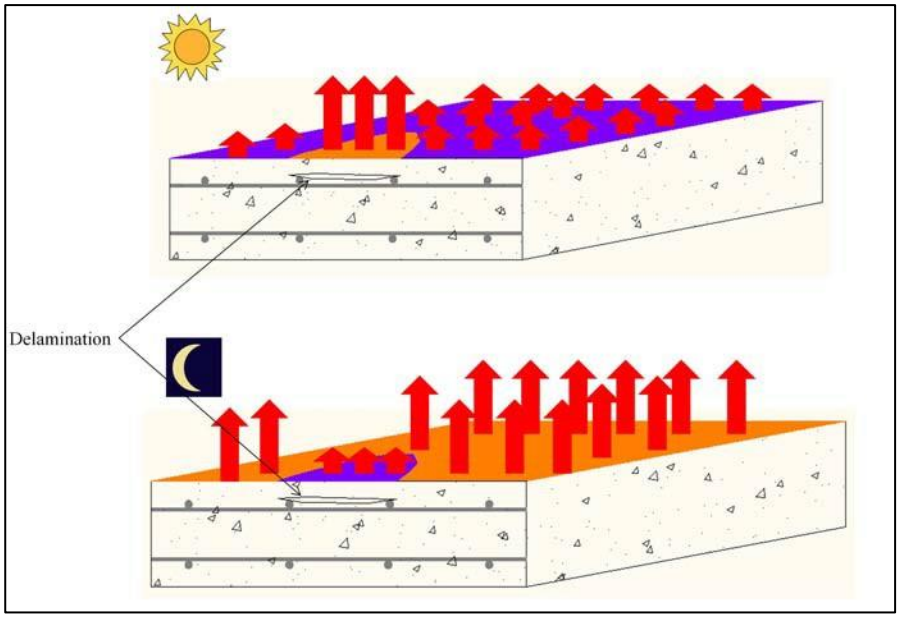

Figure 2-2: Emitted Thermal Infrared Energy from a Concrete Deck during the Day and Night.

Infrared thermography has the potential to be and effective inspection technique on both the top and bottom surfaces of the concrete bridge deck as well as other concrete elements such as prestressed or reinforced concrete girders and piers.

2.1.4.1. 1 Application to Bridge Decks

Infrared thermography has been cited in the ACI 222 report as a potential tool for detecting delaminations (ACI 2001). Additionally ASTM D4788 describes the test method, equipment and environmental conditions for detecting delaminations on the topside of the concrete bridge decks using this technology (ASTM 2007). This remote sensing technology can yield both qualitative and quantitative indicators of condition. A delamination map, created from the outputs of a thermal IR bridge inspection, can help to document relative shapes of these indicators and can be used to determine the total area and percentage of delaminations over the entire bridge deck.

According to the ASTM D4788 – *Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography*, a thermal IR camera (0.1˚F thermal resolution), video recorder, video camera, distance measurement device, test vehicle and contact thermometer are required for passive infrared thermography testing over the bridge deck. The thermal IR camera is mounted to a vehicle along with a video camera in a way that provides a minimum image width of 14ft. The vehicle mounted thermal IR camera and a video recorder are driven over the center of each lane on a bridge deck at near highway speeds while assessment information is acquired. The conventional video camera images are integrated with corresponding infrared images on the bridge deck to separate patches and surface defects from subsurface defects. From the collected information, image processing techniques are performed and delamination maps are prepared. These maps are then georeferenced to corresponding locations on the bridge deck and a composite image is generated. Bridge deck dryness is a factor that has to be considered during data collection with this method, as moisture on the surface can affect emissivity and reduce the thermal contrast on the thermal IR image (ASTM 2007).

Time of data collection is the most critical factor in a thermal IR survey. Different materials in the environment have different responses to ambient temperature change and this causes the variation in diurnal radiant temperature measures for different materials. Two thermal crossover times can be identified in the diurnal graphs of radiant temperature of materials. These two times are roughly the local sunrise and local sunset time; when the radiant temperatures of the materials are the same and appear with the same temperature on the thermal IR image. Concrete materials and delaminated areas on a bridge have similar behavior with respect to ambient temperature changes. In a study conducted by Washer et al. (2009) on developing thermal IR inspection technology for concrete bridges, it was found that the effective time to perform a thermal IR test depends on the depth of the delamination. The most contrast appears on the thermal IR image approximately 4 hours after sunrise for a 2 in. deep delamination and 7 hours after sunrise for a 3 in. deep delamination (Washer et al. 2009 a).

2.1.4.1.1.1 Advantages

Capable of detecting subsurface defects and delaminations, commercial availability, remote sensing, and ease of data collection and image interpretation are the advantages of the passive infrared thermography technique. This method of condition assessment provides an objective methodology to detect subsurface defects that is independent of inspector training and experience. In addition, inspection time is significantly reduced making this assessment technique less disruptive to traffic routes than other methods such as closing lanes to conduct hammer soundings. These advantages and the fact that infrared thermography provides in-depth condition information highlights the benefits of applying this technique in biennial bridge inspection practices (Ahlborn et al. 2012). Lab studies of passive infrared thermography for concrete slabs show that this technique is capable of detecting shallow (up to 3 inches from the top surface) delaminations which can help bridge inspectors identify areas of unsound concrete before they turn into spalls (Ahlborn et al. 2012).

Evaluating the top subsurface of concrete bridge decks has been mentioned in the literature as the main application of passive infrared thermography for bridge inspection as this element is exposed to direct sunlight (Gucunski et al. 2013). This technology also has the potential to be applied at near highway speed over the bridge deck with more advanced cameras, which can help to conduct quicker, safer, more frequent inspections. Another advantage associated with the use of infrared thermography is that the results from a delamination survey can typically be easily imported and stored in a standard GIS software such as ArcGIS, thus enabling a bridge management team to review the bridge information easier for decision making (Ahlborn et al. 2012).

2.1.4.1.1.2 Limitations

Previous studies on passive infrared thermography applications for bridge inspection have reported several limitations that should be considered. Clark et al. highlighted the fact that emissivity of the concrete surface can vary based on different materials found on the surface, thus the appearance of what might seem like a subsurface defect on thermal images is not necessarily an indication of such defects (Clark et al. 2003). Soil, moisture, oil spills, and staining on the concrete surface can appear as hot spots and affect the results of passive infrared thermography; therefore, taking optical (visual) images of the concrete surface is necessary to enable the inspector to separate these areas from delaminations.

Wind speed, solar energy, ambient temperature and humidity are environmental factors that influence thermal IR images (Washer et al. 2009 b). More advanced thermal IR camera models have the option to adjust the image based on the relevant humidity and ambient temperature occurring at the time of data collection. The minimum ambient temperature of 32˚F and the maximum wind velocity of 30 mph have been defined as upper limits on environmental criteria for performing passive infrared thermography of concrete bridge decks in ASTM D4788 (ASTM 2007). Washer et al. investigated the effects of variable environmental conditions on concrete bridge inspections and suggested a maximum wind speed of 8 mph on a sunny day and 10 mph when the surface is not directly exposed to solar energy. Also, it has been noted that consistent solar loading on the concrete can provide a better contrast on a thermal IR image (Washer et al. 2009 b).

Infrared thermography inspection is mostly applied for shallow delaminations. The maximum depth of 3 inches has been mentioned in the literature as a limitation of this technology in detecting delaminations (Vaghefi et al. 2013). When interpreting a thermal IR image, consideration must be taken to the fact that temperature variations of subsurface defects decrease with depth.

Determining the quantitative measures with passive infrared thermography is also a challenge that has to be considered while analyzing the results. Although generally more variables are involved in conducting a passive infrared thermography test, some previous studies suggest that

processing methods that are applicable for active thermography tests have the potential to be used for passive thermography as well (Abdel-Qader et al. 2008).

2.1.4.1.2 Application to Fascia Beams and Underside

Several studies have demonstrated that passive infrared thermography can also be applied for detecting deterioration on the deck bottom surface and on the bridge soffits (Washer 2010). Locating and mitigating damaged areas can be critical for the safe passage of traffic under the bridge.

Although most of the previous field applications of the infrared thermography in civil engineering have focused on passive thermal IR techniques, Pollock et al. (2008) investigated the possibility of using external heaters as part of an active thermal IR system to warm up prestressed concrete bridge girders before collecting the thermal IR images. Two methods were considered to perform this test on the bridge. In the first method, a heater was placed inside the prestressed box girder and thermal IR images were taken from the external box girder surface underneath the bridge. In this method, irregularities appeared as cold spots in the thermal IR images. Performing this test with this method is not always possible, as it requires access inside the box beams. The second method involved heating the underside of the bridge box girders by placing a heater on a lift truck platform and heating the girders for one to three hours before taking thermal IR images. Both of these methods showed promise for detecting delaminations in prestressed girders; however cost and accessibility are two factors that need to be considered in applying active thermal IR imaging for bridge inspection (Pollock et al. 2008). A variety of controllable heating sources, including hot air guns, quartz lamps and heat blankets can be used to produce thermal excitation on the test specimen. Solar energy has been mentioned by some researchers as a potential external heat resource (Spring et al. 2011).

2.1.4.1.2.1 Advantages

Remote sensing characteristic of infrared thermography can reduce traffic disruption and lane closures on and specifically underneath the bridge, as no direct contact is required. This allows for the inspector to collect condition information from a distance, either from a moving vehicle or outside of the traffic lanes. Previous study shows that passive thermography can be easily applied for inspecting fascia beams from the shoulders and without using an aerial truck (Ahlborn et al. 2012). Figure 2-3 shows a possible delamination on the fascia beam of Willow Rd. as collected form a hand held thermal camera.

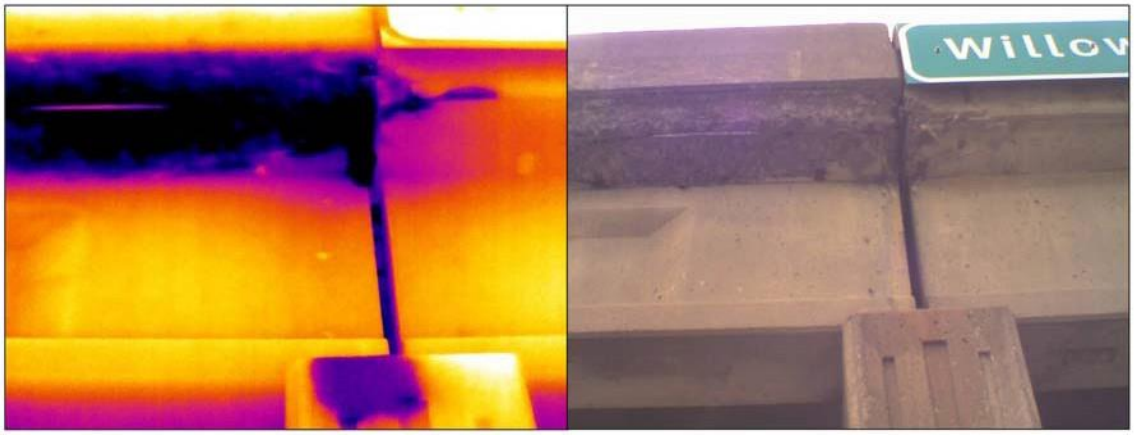

Figure 2-3: Thermal Infrared and Digital Image of Fascia Beam (Willow Rd. bridge August 2011).

Using active infrared thermography for under the deck and fascia beams inspection enables bridge inspectors to determine the location, size and depth of delamination. This condition assessment technique is not dependent on solar radiation to create a temperature difference; therefore, it allows conducting a bridge inspection in a larger time window. Furthermore, active infrared thermography can significantly facilitate inspection of concrete bridge elements that are not exposed to the direct sunlight, such as the underside of a bridge deck.

2.1.4.1.2.2 Limitations

Speed of data collection is one of the main limitations of application of infrared thermography under the bridge deck. It is generally not possible to collect data under bridge decks from a moving vehicle; a data collector has to take the thermal infrared sensing device and point it at areas above them to collect information. Taking thermal infrared images from the shoulders is most common in applying this technology for bridge soffits, however, viewing angle is one of the factors that can affect emissivity and has to be considered in interpreting thermal infrared images, (Washer 2010). In addition, deploying this technology underneath the bridge is dependent on the amount of solar energy that can be absorbed in the bridge deck during the day and may not be as effective for areas closer to the centerline. Therefore, an active heating system may be required for such in-depth inspection. Other factors such as cost and delamination depth may influence the applicability of this method as well. Equipment costs can ranges from $5,000-$50,000, and delamination depths greater than 2 in. can be difficult to identify.

2.1.4.2 Electro-Optical

Electro-optical (EO) sensors are those electronic sensors that are sensitive to electromagnetic radiation in the visible spectrum. The most common EO sensors are Charge-coupled Devices (CCDs) and are used in a typical consumer-grade digital camera. The wide scale availability of digital cameras and low cost make them a good candidate for characterizing condition

information of bridges. Aside from acquiring photo inventories of spalls and other condition information, the photos taken can also be used to extract additional, three-dimensional, information through photogrammetric techniques.

Photogrammetry is "The science or art of deducing the physical dimensions of objects from measurements on photographs of the objects" (Henriksen 1994). This includes measurements made from both film and EO (digital) photography. Digital photogrammetry has been demonstrated as a viable technique for generating 3D models of structures and structural elements (Maas and Hampel 2006). In order to perform 3D photogrammetry, the photos need to be taken with at least a 60% overlap (McGlone et al. 2004). This ensures that a feature on the ground is represented in at least two photos. Figure 2- shows the process of collecting stereoscopic imagery.

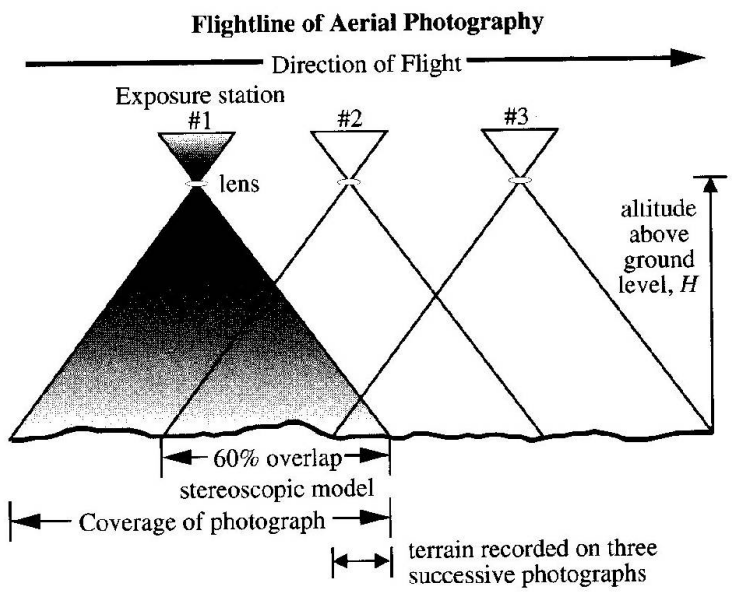

Figure 2-4: An Example of How Stereoscopic Imagery for Generating 3D Models is Collected (Jenson 2007).

Traditionally, photogrammetric techniques have been applied to aerial photography. For the purposes of collecting high resolution imagery of bridges close range photogrammetric techniques would have to be applied. Close range photogrammetry is defined as capturing imagery of an object or the ground from a range of less than 100 m (328 ft) (Jiang et al. 2008). This method can be used to generate 3D models of bridge decks from which condition information is extracted as described by Ahlborn et al. (2012).

2.1.4.2.1 Application to Bridge Decks

This technology can be used to detect spalling on the bridge deck as well as generate a photo inventory and composite image of the deck through a vehicle mounted camera (Ahlborn et al. 2012). Spall detection and a photo inventory are achieved through two different systems. To

create a photo inventory of a bridge deck, a pair of cameras mounted on the front of a vehicle provides sufficient coverage of the vehicle lane. A high resolution composite image of the bridge and a 3D representation of the bridge surface are generated by collecting stereo pair imagery through a camera mounted facing straight down and are used to located and quantify spalls.

Condition information can be extracted from the Digital Elevation Models (DEMs) generated as well as from the raw imagery. However, the condition information is limited to surface features such as spalling and cracks. These features can be detected either through manual interpretation of the imagery or through automated means using a combination of the DEM and imagery. This data can then be integrated with other geospatial data in a GIS or Decision Support System (DSS) to assess broader condition information (Ahlborn et al. 2012).

2.1.4.2.1.1 Advantages

3D Photogrammetry can provide accurate measurements of bridge deck surface condition while minimizing traffic disruptions. By mounting a camera to a vehicle and collecting stereo pair imagery, 3D models are generated to extract condition information such as spalling and cracks. This technology is less expensive than other spatial rendering systems such as the ability to generate high resolution DEMs (Ahlborn et al. 2012). Images collected from this system can also be mosaicked together to form a high resolution composite image of an entire bridge deck to assist with condition rating and visualizing the location of spalls in a GIS (Ahlborn et al. 2012).

This technology can be applied to near highway speeds by using a camera capable of faster frame rates than the first generation 3DOBS system developed in 2011. Higher resolutions can be achieved by choosing a camera with a larger sensor (i.e. more pixels) and a higher quality lens. With the wide availability of cameras and lenses these systems are not limited to a few dedicated and specialized sensor options, which helps to keep cost down.

2.1.4.2.1.2 Limitations

The main speed limiting factor with using close range photogrammetry is with the camera and lens performance. Image quality is directly related to the frame rate, shutter speed and resolution of the camera. Image resolution is a function of the camera sensor, the quality of the lens being used and the shutter speed. The frame rate is determined by the shutter speed and the available lighting. The resolution and rate at which the camera takes pictures limits the size of the distress that can be detected and the speed at which a system can be driven across a bridge deck. An example from Ahlborn et al. is of the Nikon D5000 used that had a sensor that was 12.3 MP (Mega Pixels) with an 18 mm focal length lens. The field of view covered one full road lane and a digital elevation model (DEM) with a resolution of 5 mm was produced. This system was limited by the continuous frame rate of more than 1 frame per second. This limits the speed of the vehicle to 2 mph to achieve the required image overlap. However, faster

cameras should enable collection speeds of at least 45 mph. Logistics and costs of data storage must also be considered.

This system is also limited by lighting and weather conditions. Water or snow on the road surface fills spalls and cracks resulting in incorrect defect detection. Under low light conditions, in order to properly expose an image the shutter speed is lowered to allow for more light to reach the sensor however this would require lower vehicle speeds to reduce motion blur. Testing shows that a Nikon D5000 operating at one frame per second can collect sufficient close range photogrammetry under most natural lighting conditions. (Ahlborn et al.2012).

2.1.4.2.2 Application to Fascia Beams and Underside

EO techniques can also be used to generate photo inventories and 3D models on bridge fascia beams and undersides. Imagery of the underside of the bridge can be collected through a vehicle mounted camera similar to the bridge deck except the camera is mounted facing up, although it is generally not possible to easily drive the entire longitudinal length of a bridge.

2.1.4.2.2.1 Advantages

The current condition of fascia beams and the underside of a bridge can be captured by vehicle mount camera systems. Photo inventories can be collected for both bridge components. Figure 2-5 shows a series of photos taken of the underside of a bridge with the deck bottom and the bottom of the beams clearly visible. These photos could be used as a photo inventory showing the location of a delamination (green square) that has been detected with other technologies (Ahlborn et al. 2012). 3D photogrammetry can also be used to generate 3D models of the fascia beams and portions of the underside from the stereo pair imagery. Figure 2-6 and Figure 2-7 show a model of the Silverbell Rd. box beam that was removed.

Figure 2-5: Photos taken with 3DOBS of the Underside of Willow Rd. Bridge (Ahlborn et al. 2012).

Figure 2-6: A Composite Image of the Silverbell Bridge Box Beam Derived from Stereo Imagery.

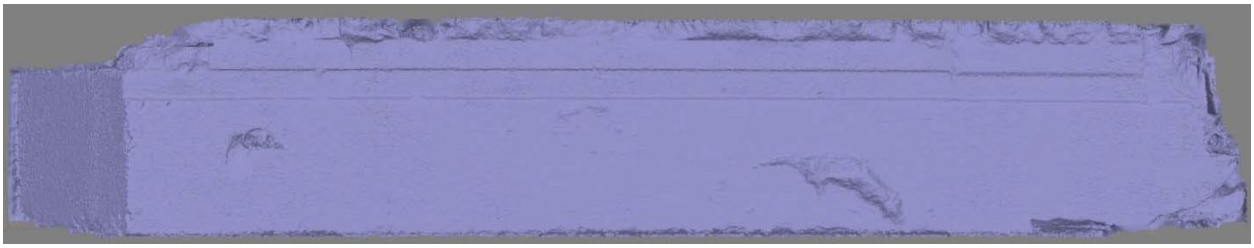

Figure 2-7: 3D Model of the Silverbell Bridge Box Beam Derived from Stereo Imagery.

2.1.4.2.2.2 Limitations

For the collection of imagery of fascia beams, overlapping photos are taken along the length of the beam. This would be difficult for a vehicle mounted system to achieve while driving with traffic. Models can be derived if overlapping imagery is taken along the length of the beam from a stationary camera. As seen in Figure 2-5, the sides of the beams are not visible in the photos taken with a vehicle mounted system.

While an EO system can collect imagery of the underside of a bridge with a vehicle mounted system, a complete model of the beams or underside of a bridge deck could

not be generated (Ahlborn et al. 2012). This is due to the viewing geometry between the cameras and the sides of the beams, how close the beams are to each other and whether at least two overlapping images can be collected. The closer the beams are to each other or the taller they are, the less information can be collected on the sides of the beams. This limitation also applies to the underside of the bridge deck, as the camera needs to be able to collect overlapping images. Due to viewing constraints, models of the underside would be limited to only the bottoms of the beams and parts of the underside of the bridge deck.

2.2 Applications of the Current State of Research and Practice

Applications of remote sensing technologies for bridge condition assessment are limited. This section provides an overview of the current state of research using some remote sensing options most applicable to bridge deck condition assessment. While some technologies are more mature, others have yet to be proven for concrete deck evaluation. Several projects are described below to broaden the reader's knowledge of the current state of remote sensing technology for use in the condition assessment of concrete bridge decks.

2.2.1 USDOT/RITA projects

The Michigan Tech Transportation Institute (MTTI) and Michigan Tech Research Institute (MTRI), in cooperation with the Center for Automotive Research (CAR) and the Michigan Department of Transportation (MDOT), completed a research study exploring the use of remote sensing technologies to assess and monitor the condition of bridge infrastructure and improve the efficiency of inspection, repair, and rehabilitation efforts. This project was sponsored by the United States Department of Transportation (USDOT) Research and Innovative Technology Administration (RITA) Commercial Remote Sensors and Spatial Information Program (Ahlborn et. al, 2012).

3DOBS and passive infrared thermography techniques were studied and deployed on four prestressed concrete I-girder bridges in Michigan in August 2011. Field inspection on these four bridges was conducted at speeds slower than traffic.

The aim of the field demonstration selection process was to identify bridges that had varying degrees of degradation with the potential to be identified and quantified using multiple remote sensing technologies. Four bridges were selected based on their assigned current NBI condition rating. Upon completion of the bridge selection discussion, three field demonstration locations had been established, each fulfilling the selection parameters for the three separate categories. The bridges selected were as follows:

- "Poor" condition; Mannsiding Road over US-127 north bound (NB)
- "Fair" condition; Willow Road over US-23
- "Satisfactory" condition; Freer Road over I-94

2.2.1.1 Mannsiding Rd. Bridge

The selected "Poor" condition bridge, MDOT structure No. 1713 – Mannsiding Road over US-127 north bound, is located in Clare county approximately ten miles north of Clare, Michigan. The structure is 130.92 ft in length and 31.17 ft in width, which translates into 26 ft of riding surface. During 1996, the average daily traffic (ADT) over the structure was found to be 1,000 with 3% being commercial. The condition of the concrete deck surfaces, both top and bottom, were an area of major concern. A 2008 MDOT scoping inspection classified the deck with a NBI rating of "4". The scoping revealed that on the top surface of the concrete deck 176 ft^2 or 4.4% of the deck was delaminated. Additional testing on the bottom surface revealed that 623 ft^2 or 15% of the deck was in distress. False decking was present when visited in 2011. The deck also possessed light scaling throughout and numerous transverse, longitudinal and diagonal cracks were present. Additionally, several high-load hits have resulted in scrapes and spalls of the superstructure underside, but currently there is no sign of exposed reinforcing steel or pre-stressing strands. The bridge is scheduled for complete replacement in 2012/13. Additionally, during the on-site inspection of the selected "Poor" bridge, its complementing twin bridge, Mannsiding Road south bound overpass was also visited. The Mannsiding Road south bound overpass bridge is described in further detail in the "Supplemental" bridge selection section.

3DOBS and infrared thermography results for this bridge were imported in ArcGIS and are shown Figure 2-8 and Figure 2-9, respectively. The total spalled area on Mannsiding Road bridge was 1.73 m^2 (18.62 ft^2) which is 0.47% of the entire bridge deck surface. Chain drag results showed 127.3 ft^2 (3.63% of the total bridge deck area) total delaminated areas on the bridge deck, while the total delaminated area calculated from thermal infrared imagery survey was 136.13 ft^2 (3.88% of the total bridge deck area).

Figure 2-8: A) Mannsiding Road Bridge Digital Elevation Model (DEM) and Spall Map Layer on ArcGIS, B) Mannsiding Road Bridge Spall Map Generated with Spall Detection Algorithm.

Figure 2-9: Combined Results of Thermal IR Imagery Chain Drag Inspection.

2.2.1.2 Willow Rd. Bridge

MDOT structure No.10892 – Willow Road over US-23 was selected for the "Fair" condition field demonstration bridge. The bridge is located in Washtenaw County approximately three miles north of Milan, Michigan. The bridge was constructed in 1962 and is a 4-span prestressed concrete multiple I-beam composite structure. The structure is 209 ft in length and 30.83 ft in width, which translates into 26 ft of drivable surface with no availability for shoulder room. During 1997, the ADT over the structure was found to be 2,220 with 3% being commercial. The current condition of the deck surface is rated as a "5" on the NBI scale. In 2010, the inspection report indicated that open transverse cracks, diagonal cracks and areas of delamination were present throughout the deck. Concrete patching had been completed to help minimize deterioration and prolong the service life of the bridge. Additionally, areas on the bridge superstructure displayed desired sensing deficiencies over both the north and south bound lanes. This is attributed to several high-load hits, which had resulted in scrapes and spalls, but there was no sign of exposed reinforcing steel or prestressing strands.

Figure 2-10 and Figure 2-11 shows the results of 3DOBS and infrared thermography of Willow Rd. bridge, respectively. Total area of spalls on this bridge was 27.3 m^2 (293.7 ft^2) which was 5.15% of the entire bridge deck surface. Hammer sounding results showed 159.5 ft^2 (3.05 % of the total bridge deck area) total delaminated areas on the bridge deck, while the total delaminated area calculated from thermal infrared imagery survey was 157.83 ft^2 (3.02 % of the total bridge deck area).

Figure 2-10: Willow Road Bridge Digital Elevation Model (DEM) and Spall Map Layer on ArcGIS.

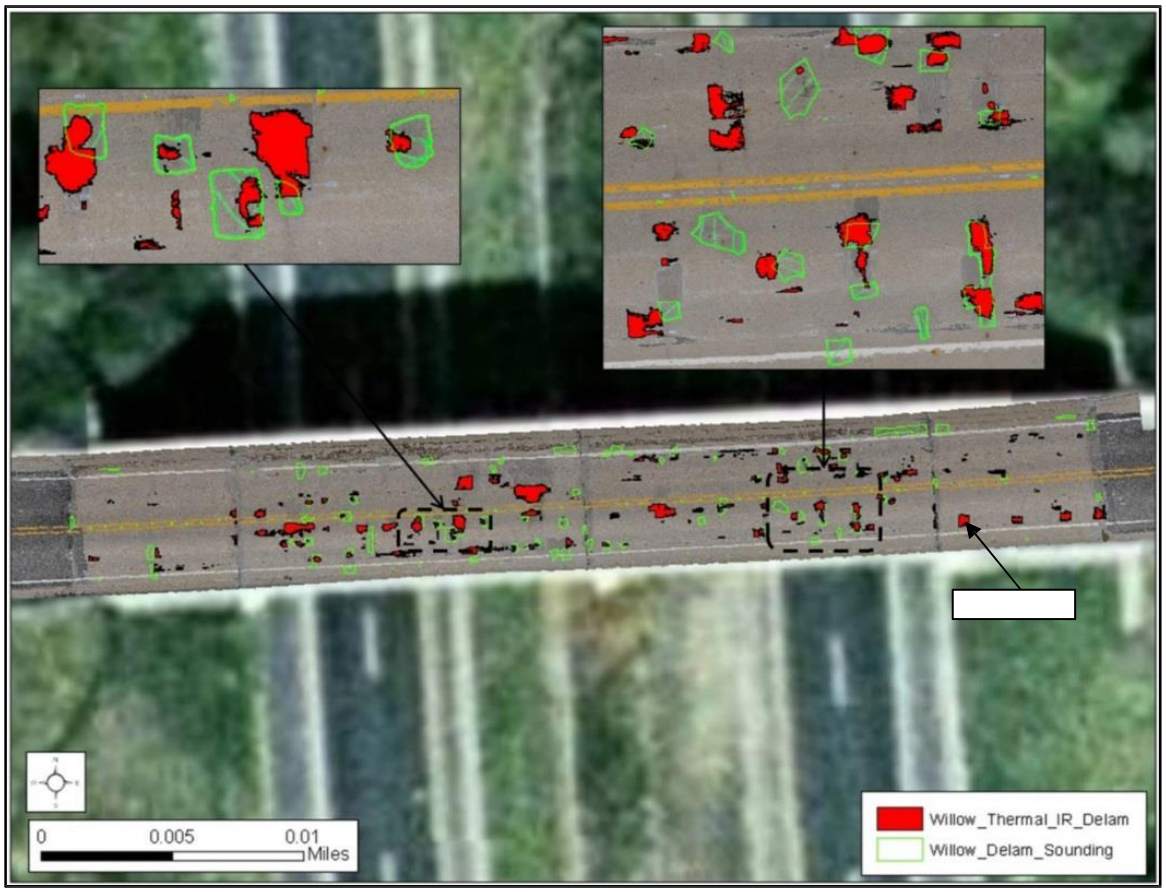

Figure 2-11: Combined Results of Thermal IR Imagery and Hammer Sound Inspection.

2.2.1.2 Freer Rd. Bridge

The "Satisfactory" bridge was chosen to be the MDOT structure No.10940 – Freer Road over I-94, located in Washtenaw County, approximately one mile east of M-52 in Chelsea, Michigan. The bridge was constructed in 1960 and is a 4-span prestressed concrete multiple I-beam composite structure. The structure is 209 ft in length and has a 28'-10" roadway opening including two 11'-0" lanes and two 3'-5" shoulders on each side. During 1997, the ADT over the structure was found to be 150 with 3% being commercial. The NBI rating assigned to the concrete deck surface is a "6". In 2010, the inspection report indicated that there were several areas of concrete patching accompanied by few tight transverse and diagonal cracks present on the deck.

Figure 2-12 and Figure 2-13 shows the results of 3DOBS and infrared thermography of Freer Rd. bridge. Total area of spalls on this bridge was 3.8 m^2 (40.1 ft^2) which is 0.67% of the entire bridge deck surface. Hammer sound results showed 101.74 ft^2 (1.8 % of the total bridge deck area) total delaminated areas on the bridge deck, while the total delaminated area calculated from thermal infrared imagery survey was 29.25 ft^2 (0.52 % of the total bridge deck area). The main cause of variation between the results of the hammer sounding and infrared thermography surveys on the Freer Road bridge is that most of the delaminations on this bridge were around the construction joint and overlapped with the painted centerline on the bridge deck. Reflective paint on the bridge deck has lower emissivity than concrete; therefore, it will appear on the thermal IR image with lower temperature and cause some difficulties in detecting delaminations in those areas.

Figure 2-12: Freer Road Bridge Digital Elevation Model (DEM) and Spall Map Layer on ArcGIS.

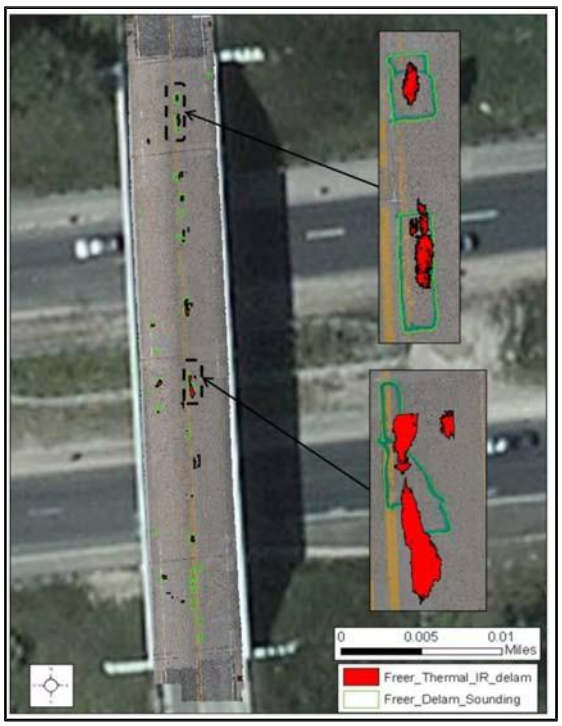

Figure 2-13: Combined Results of Thermal IR Imagery and Hammer Sound Inspection.

2.2.2 BridgeGuard projects

In February 2010, the BridgeGuard framework of passive IR bridge deck image collection and analysis was described in a two-part article in Roads and Bridges magazine (Howard et al. Feb 2010; Howard and Sturos March 2010) The article explored IR technology as a contributing solution to the detection and mapping of concrete bridge deck delaminations. Article 1 re-affirmed previous assertions that (IR) is a valued tool in the application of bridge deck NDE and provided the rationale for the development effort of a dedicated off-the-shelf tool. Article 2 explained how this development proceeded and what capabilities resulted within the BridgeGuard framework. Examples of BridgeGuard case studies are included in this report to show the current stage of the application of infrared thermography on bridges.

2.2.2.1 Oceana County Bridges, Michigan

BridgeGuard, Inc. (formerly Talon Research) conducted infrared thermography surveys on five bridges in Oceana County, MI. The selected bridges were scanned numerous times on several occasions to evaluate and improve calibration of GPS-based imaging frequencies and to improve test protocol in varying weather conditions and collection times. All these five bridges are steel girder bridges with concrete deck.

1) MDOT structural No. 8328 – Webster Rd. Bridge over US-31,
2) MDOT structural No. 8329 – Winston Rd. Bridge over US-31

3) MDOT structural No. 8332 – M20 EXT Bridge over US-31
4) MDOT structural No. 8344 – Hayes Rd. Bridge over US-31 (SB)
5) MDOT structural No. 8345 – Hayes Rd. Bridge over US-31 (NB)

The five bridges evaluated had an average length of 280 feet with an average width of 24 feet. The results of the bridges varied in total delamination percentages as well as total number of delaminations. The highest number of delaminations found in a single bridge was 202, this highlighted obvious visible patches and man-made saw cuts. This bridge registered a total percent of deck delaminations of 14.26%. The lowest number of delaminations found in a single bridge was 24 for a bridge-total percent of 1.77%.

2.2.2.2 Cedar Key Bridge, Florida

BridgeGuard, Inc. conducted an infrared thermography survey on Cedar Key Bridge in Florida, which was built in 1972. The bridge overall length is 952 feet long by 44 feet wide with substructure elements consisting of 20 bents with 7 – 22 inch square piles per bent. As part of the validation and ground truth process, a hammer was used to assist in outlining a targeted sub-surface flaw. A chalk outline was marked on the cap and a visual image was taken showing the chalk outline of this hammer-measurement (Figure 2-14). Also shown is the spatially corresponding IR image taken at 0800 hours on November 7, 2010 (Figure 2-14) illustrating the geometrics of the bridge cap and the outline of the characterized delamination. A qualitative correlation can easily be made by the reader between the IR image and the actual physical measurement shown in the visual image. It is noted that, while not visible in either image, this delamination extended up and around the opposite side vertical surface of the cap.

Figure 2-14: A) Visual Image of Marked Delamination on the Bridge Cap and B) Thermal IR Night Image of Delamination.

3. System Upgrades and Lab Testing

Our pace of technology is advancing rapidly in the past five years. Since completion of the USDOT/RITA study in 2012 (*Bridge Condition Assessment Using Remote Sensors*), commercially available cameras have enhanced performance with increased frame speed for use at near highway speeds, in addition to a lower cost and improved ease of data processing for evaluation of health condition indicators. This chapter describes the equipment and system upgrades used for the evaluation of the top of concrete bridge decks. Chapter 6 presents the system used to evaluate the bottom surface of the deck and field demonstration results.

Passive thermal imaging and a 3-D Optical Bridge-evaluation System (3DOBS, an application of 3-D photogrammetry) were combined for detecting spalls and delaminations on the top deck surface at near-highway speeds (see Chapter 5). Passive thermography is a more mature technology used to locate suspected delaminations and is capable of operating at highway speed. The 3DOBS system, previously used at walking speed, was implemented at near highway speed to detect spalls using a lower resolution camera system. Using a higher resolution system and slower speeds, crack size and location was investigated. In addition, the Bridge Viewer Remote Camera System (BVRCS), also an optical system using Go-Pro cameras, was enhanced to provide a high-resolution photo inventory of the top deck surface while travelling at near-highway speed.

3.1 3DOBS

3.1.1 Near Highway Speed

In order to take the original version of 3DOBS, which was limited to 2mph, to near highway speeds a new camera had to be used. There are two main camera characteristics that limit the collection speed. The first is the maximum sustained frame rate, in frames per second (fps), of the camera. The Nikon D5000 is only capable of 1 fps for continuous shooting which is not sufficient for faster speeds. Frame rate determines how much overlap there will be in the imagery at a given vehicle speed.

The Nikon D5000 used previously was able to capture a full lane width per pass (Ahlborn et. al, 2012). From 9 ft above the bridge deck the field of view (FOV) was approximately 8 ft x 12 ft with an 18 mm focal length lens. In order to achieve at least 60% overlap in the collected imagery at that FOV, an image needs to be collected every 3.2 ft across the bridge deck. For data collection while traveling at 45 mph with a camera with a similar FOV, the camera would have to capture imagery at a frame rate of at least 21 fps (Table 3-1).

Table 3-1: Required Camera Frame Rate for Variable Vehicle Speed.

Speed (mph)	Distance Between Shots (feet)	Frame Rate Needed (fps)
1	3.2	0.46
5	3.2	2.29
10	3.2	4.58
15	3.2	6.88
20	3.2	9.17
25	3.2	11.46
30	3.2	13.75
35	3.2	16.04
40	3.2	18.33
45	3.2	20.63
50	3.2	22.92

The other characteristic is shutter speed. On digital camera this refers to how long the sensor collects light for an image. In typical photography, shutter speed is adjusted to achieve properly exposed images where shutter speed is decreased for low light and increased for bright lighting conditions. For 3DOBS, shutter speed also plays a role in minimizing motion blur. Motion blur typically occurs as the object is moving across the FOV of the camera as the sensor is collecting. This degrades the sharpness of the resulting imagery and therefore reduces the quality of the resulting 3D model. If motion blur is too excessive, 3D modeling software will be unable to process the imagery all together.

In order to minimize motion blur, the shutter speed needs to be increased as the vehicle speed is increased. For the collects with the Nikon D5000 at 2 mph motion blur was not an issues even under overcast conditions. For vehicle speeds up to 45 mph motion blur will become more apparent. Because of this it is important to have a camera that has a fast shutter speed.

Table 3-2: List of Possible Cameras Considered for 3DOBS Upgrades.

Manufacturer	Model	Resolution (Megapixel)	Max FPS (at full resolution)
Nikon	D5000	12.3	4
Nikon	D5100	16.3	4
Nikon	D90	12.3	4.5
Nikon	D7000	16.2	6
Nikon	D300s	12.3	7
Nikon	D700	12.1	5
Nikon	D800	36.3	4
Nikon	D3S	12.1	9
Nikon	D3X	24.5	5
Nikon	D4	16.2	10
Canon	EOS Rebel T3	12.2	3
Canon	EOS Rebel T2i EF-S	18	3.7
Canon	Eos Rebel T3i EF-S	18	3.7
Canon	EOS 60D	18	5.3
Canon	EOS 7D	18	8
Canon	EOS 5D Mark II	21.1	3.9
Canon	EOS-1D Mark IV	16.1	10
Canon	EOS-1Ds Mark III	21.1	5
Canon	EOS-1D X	18.1	12
RED	Scarlet-X	13.8	30
RED	Epic	13.8	60
Sony	F55	8.9	60

Based on research existing DSLR cameras, none of them are capable of the frame rates necessary for a near highway speed version of 3DOBS. The fastest (listed in Table 3-2) are capable of up to 10 fps. Actual sustained frame rates tend to be lower as observed by the project team. The Nikon D5000 is rated at 4 fps but for continuous shooting longer than 30 seconds, it exceeds the buffer capacity and is unable to continue at that speed. Therefore a max frame rate of 1 fps can be achieved without hitting buffer limitations and the camera will continue capturing imagery at 1 fps until the memory card is filled.

Since DSLRs are limited in their frame rate, the project team looked into other, faster camera types. For this, cameras that are traditionally used for the movie industry were investigated. These offer better than HD video quality (> 2 MP per frame), at frame rate exceeding 24 fps. The Sony F55 and the RED Epic cameras were researched as potentially suitable cameras for the near highway speed camera. Since it was necessary to have a resolution of at least that of the Nikon D5000, the RED Epic was chosen to test with a max resolution of 13.8 MP per frame.
A RED Epic was rented at first to test the cameras capabilities and if it would work as a suitable replacement for a near highway speed version of 3DOBS. Since the camera with all of its needed accessories would cost at least $25,000 it was necessary to make sure the camera performed as needed before purchasing. Therefore, a one week trial was conducted in June 2013 to collect

imagery over Freer Rd. The RED Epic was able to collect imagery with minimal motion blur at vehicle speeds of 45 mph (Figure 3-1).

Figure 3-1: An Extracted Frame from the June 2013 RED Epic Test over Freer Rd. This Image Shows very Little Motion Blur and would be Acceptable to run through Agisoft.

During the test runs the weather conditions were mostly sunny which allowed for the maximum shutter speed of 1/8000 sec to be used. With a fast shutter speed, motion blur was reduced to the point that it did not cause an issue with processing. Based on the successful testing of the RED Epic, it was purchased as the 3DOBS near highway speed camera.

3.1.2 High resolution crack detection

In order to detect cracks, frame rates were not as important as resolution of the camera. More pixels allow for greater coverage of the field of view and therefore a high resolution of the surface being imaged. For crack detection, the Nikon D800 was chosen since it had the highest camera resolution of 36.3 MP while other cameras were limited to less than 25 MP (Figure 3-2).

Figure 3-2: Nikon D800.

Lab testing of the Nikon D800 had to be performed in order to determine the actual resolution of the camera. Since different lenses and other factors play a role in actual resolution, these include the lens diffraction coefficient, aperture setting (f-stop), lens distortion, distance to target / focal length, bayer pattern (RGB sensor array that constitutes a single pixel), amount of pixels and JPEG compression. These variables are different for every camera and even between different collects depending upon the lighting. Testing in the lab under controlled conditions had to be performed first to understand these variables.

These tests were conducted using a camera calibration chart to compare the Nikon D800 to the Nikon D5000 which was used previously. Photos were taken from 9 ft away using the same lens set to 18mm focal length. The cameras settings were set the same for both so that the only variable was the number of pixels of each cameras sensor.

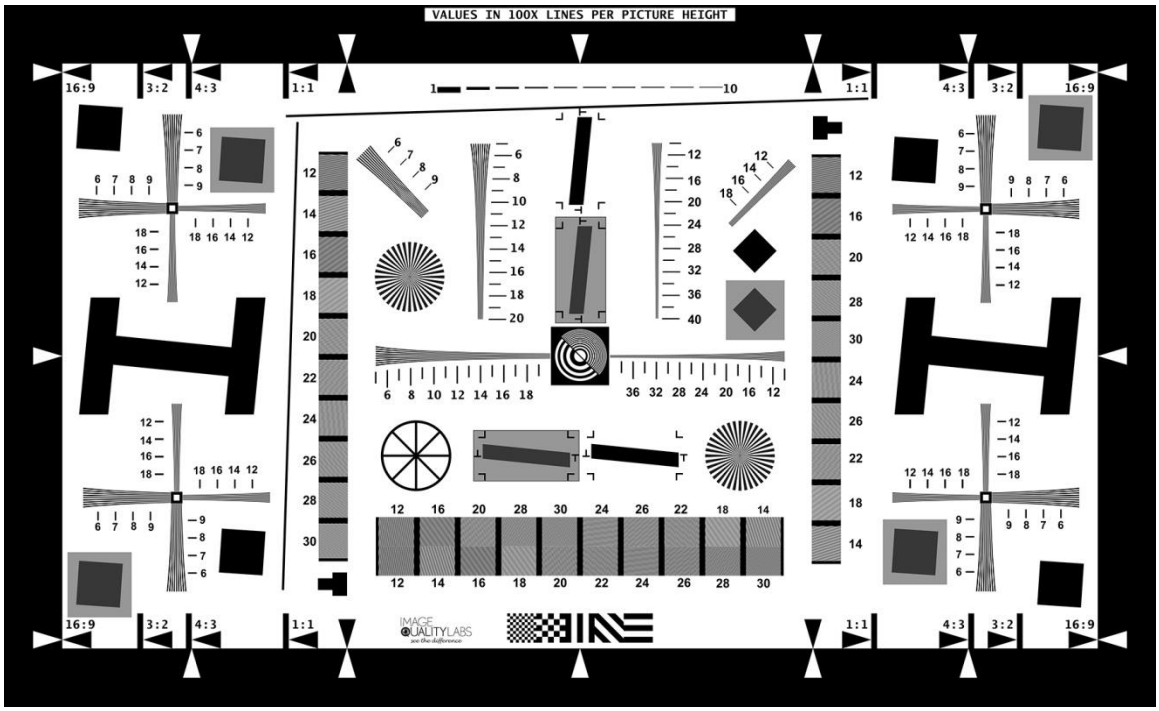

Figure 3-3: Resolution Chart for Testing Camera Resolution.

The images collected by each camera are compared in Figure 3-4. It is shown that the Nikon D800 captures clearer imagery than the Nikon D5000 which was expected. After careful analysis of the limits of each camera to resolve the separation between two lines, it was determined that the resolution of the Nikon D5000 under these conditions was at least 5mm while the Nikon D800 was approximately 1mm (Figure 3-5).

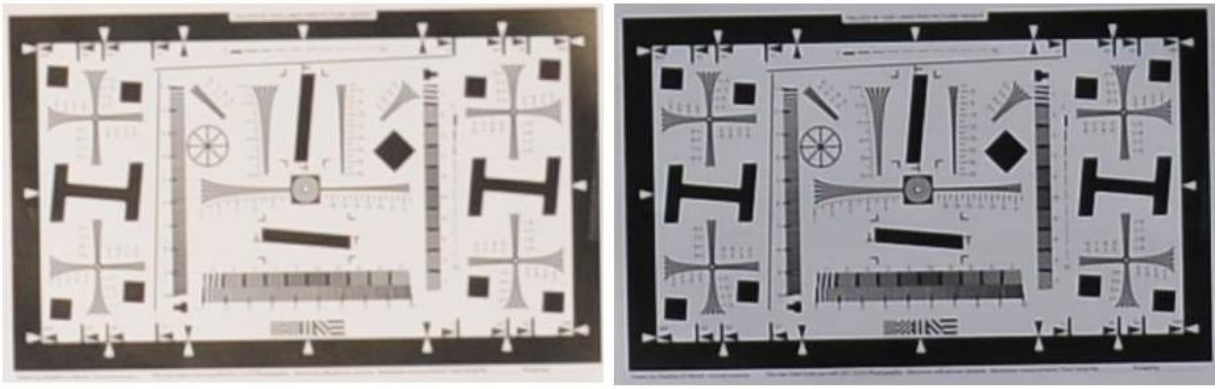

Figure 3-4: Comparison of the Imagery Collected by the Nikon D5000 (left) and the Nikon D800 (right).

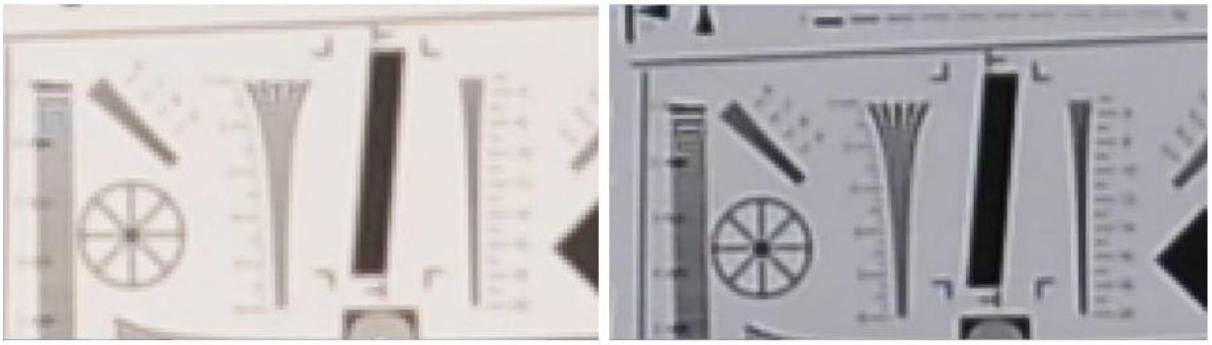

Figure 3-5: Comparison of the Ability of each Camera to Resolve the Separation between Two Lines. The Nikon D5000 is on the Left and the Nikon D800 is on the Right.

Based on this test, it was determined that under optimal conditions should capture imagery with a resolution of approximately 1mm or 1/32nd of an inch. This is higher resolution than the previous Nikon D5000 which had a resolution of about 5mm and is expected to be higher than the RED Epic which has less than a third of the pixels as the Nikon D800.

3.2 BridgeGuard Passive Infrared Thermography

3.2.1 Integration of Advanced GPS Equipment to Facilitate GIS Compatibility

BridgeGuard's fundamental enhancement challenge relative to interfacing with the 3DOBS system was, to begin precisely tagging its imagery to a geographical coordinate system such as Latitude and Longitude, at least with the precision afforded by the state of the art. Interfacing to external data sources such as the data derived from the 3DOBS system requires that BridgeGuard fully enter into and become compatible with the GIS framework. This allows a user of that data to "autonomously" map information coincidentally with external bridge data through any GIS type package.

Independent and external to this contract scope of work, BridgeGuard purchased survey grade GPS equipment that met the needs of this BridgeGuard/3DOBS integration replacing the equipment originally integrated into the BridgeGuard system. Accuracy of coordinates from a commercial grade GPS unit was problematic from several perspectives including:

- Inherent accuracy of standard GPS equipment (approximately 3 meters). This was addressed by using a differential correction process received from a variety of sources. To correct this inaccuracy, integration results using real time correction with the proper equipment is greatly reduced to the order of +/- 4-6 inches (5-15cm).

- Dynamic Response of the Equipment. Commercial GPS equipment that met the needs if this integration, updates position data at a frequency of 1 hertz, which was not adequate. However, post processing methods were developed that mitigated the low resolution GPS update frequency. Using synchronous update time stamps within both data streams, we were able to autonomously identify, within the analysis

process, these update points and then perform a time based interpolation between the points. Beyond this effort, it is the short term goal of BridgeGuard to acquire and integrate a new generation GPS product thus simplifying the process and tightening up location accuracy.

Having solved the accuracy issue within the state of the art, Lat/Lon positions acquired from a GPS unit must be correlated to an image. The most difficult and challenging task, by-far, for BridgeGuard in regards to Lat/Lon positioning is to correlate the collected Lat/Lon position provided by the GPS unit to an actual pixel in an individual image. The camera and the GPS antenna were mounted in such a method that allows the GPS position to be calibrated to the center pixel of each image.

3.2.2 Integration of GPS Positional Data with 3DOBS Data Structure Requirements

BridgeGuard revised its BridgeGuard file systems to accommodate GPS coordinates for each image, as well as each delamination found in that image. This was developed as a set of post-processing software tools that allows BridgeGuard to operate when 3DOBS is not attached and to use all of the current analyses and reporting tools under that scenario. Conversely, when 3 DOBS is attached, the post-processing tools are employed to convert the data set to be compatible with 3DOBS and generic GIS systems.

In this regard, BridgeGuard now can provide geo-reference coordinates for each delamination marked in an image. To accomplish this we calculate and assign a Lat/Lon to each pixel in the image. Algorithms were written to make this conversion based on a known pixel length/width, direction of travel, and a known pixel Lat/Lon location.

Stand-alone tools were developed that will mine the BridgeGuard collection and analysis files and create a specifically formatted output file outlining all the findings on a bridge. This file can be read by the 3DOBS processing software to integrate the thermal results from BridgeGuard with those from 3DOBS. This facilitates both scenarios where BridgeGuard and 3DOBS data are collected coincidentally and where the data sets are collected independently.

3.2.3 BridgeGuard data collection vehicle modifications

Item 3.2.3 employed the necessary effort to mount the two hardware and data systems into a final test and mounting fixture. With an adjustment to the BridgeGuard boom, space and mounting structure was provided to mount the 3DOBS camera side-by-side the BridgeGuard hardware suite. The test set-up simply requires the operator to share the vehicle cab with the BridgeGuard operator and send initiation commands to the 3DOBS camera coincidental with the initiation of the BridgeGuard collection software.

3.3 BridgeViewer Remote Camera System

The BridgeViewer system was upgraded by purchasing two GoPro Hero 3 Black Edition cameras (Figure 3-6) to replace the original Cannon PowerShot SX100 IS that were not rugged, high-speed cameras. In the original version of BridgeViewer the PowerShot was connected to a laptop that ran PSRemote software to run the cameras. Through PSRemote the user adjust the camera settings, control frame rates, and see a live video feed. Altogether the system needed two cameras, a GPS, and a laptop with PSRemote installed.

Figure 3-6: GoPro Camera used to update BridgeViewer.

With the addition of the GoPros, a laptop and additional software were no longer necessary. The GoPro cameras have a time-lapse option that allows for pictures to be taken at rates up to twice a second at 12.3 MP. They can also be controlled by a wifi remote, through a Smartphone or manually on the cameras. The previous PowerShot cameras were only capable of taking 1 fps at 8 MP. Another advantage is that the GoPro's come with a waterproof case, which would allow for it to be mounted to the vehicle in all weather conditions (Figure 3-7).

Figure 3-7: Testing the GoPros Mounted to the Hood of a Vehicle during a 3DOBS High Resolution Collection on 24 Mile Rd. near Marshall, MI.

GeoJot+ is used for geotagging the images after they are collected (http://www.geospatialexperts.com/GeoJot/). This software is designed to simplify the photo-capture to mapping and reporting processes required for many data analyses with close integration with ESRI Desktop ArcMap GIS software. Once imagery is added and the track log from the GPS, GeoJot+ interpolates the location of where the image was captured between the GPS points. A separate water marked image is generated with a date/time stamp and Lat/Lon added. A GIS shapefile is also generated that can be viewed in ArcMap and references the location-tagged and watermarked image for display in a GIS environment.