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AUTHOR (Capitalize Family Name)	POSITION	ORGANIZATION	COUNTRY
Masato Matsumoto	President & CEO	NEXCO- West USA, Inc.	United States
CO-AUTHOR(S) (Capitalize Family Name	POSITION	ORGANIZATION	COUNTRY
1. Rei Huttunen 2. Kyle Ruske 3. Tyler Tep	1. Research Engineer 2. Technology Leader 3. Business Development Manager	NEXCO- West USA, Inc.	United States
E-MAIL (for correspondence)	m.matsumoto@w-nexco-usa.com r.huttunen@w-nexco-usa.com k.ruske@w-nexco-usa.com t.tep@w-nexco-usa.com		

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ABSTRACT:

Condition ratings of bridge components in the FHWA's Structure Inventory and Appraisal database are determined by bridge inspectors in the field. However, the determination of bridge condition ratings is generally subjective depending on individual inspectors' knowledge and experience, as well as varying field conditions. Recently enacted government regulations for mandatory element level inspections (AASHTO, 2013) pose a need for effective record keeping and continued observations. This paper describes the results of on-site bridge deck scanning by digital imaging and infrared thermography technologies. In this research project, three infrared cameras with different specifications were compared for effectiveness in application to bridge deck scanning from a moving vehicle. The results obtained by three different infrared cameras were compared to show how each's specifications have evident effects on the degree of accuracy in the detection of delaminations within concrete bridge decks. It can be concluded that for highway infrared inspection, the cooled infrared camera is far superior to other commonly implemented models, and a high exposure rate is critical in preventing issues like blurred imagery and subsequent false detections. The cooled model effectively doubled the window of time in which inspections can be carried out. By raising work efficiency and precision using cooled models, there are many benefits - reduction of field work hours leads to further reduction in field data collection costs. False detections and blurry images will be minimized, and with the support from the analyzing software the bridge inspection engineer gains much more intelligent data at a much faster rate.

Biography of the Author:

Masato Matsumoto is an expert on technical aspects of NDE bridge condition assessment, inspection, deterioration prediction, life-cycle expectancy and long-term highway asset management. Matsumoto is a globally recognized structural engineer, with a professional engineering (P.E.) license in the US. He is also a member of the IRF Asset Management Committee.

Bridge Deck Scanning by Infrared Thermography

Masato Matsumoto, P.E.[1]

[1]NEXCO- West USA, Inc., Vienna, Virginia, USA
m.matsumoto@w-nexco-usa.com

Rei Huttunen[2]
r.huttunen@w-nexco-usa.com
Kyle Ruske[3]
k.ruske@w-nexco-usa.com
Tyler Tep[4]
t.tep@w-nexco-usa.com

1 INTRODUCTION

Condition ratings of bridge components in the FHWA's Structure Inventory and Appraisal database are determined by bridge inspectors in the field. However, the determination of bridge condition ratings is generally subjective depending on individual inspectors' knowledge and experience, as well as varying field conditions. Recently enacted government regulations for mandatory element level inspections (AASHTO, 2013) pose a need for effective record keeping and continued observations. This paper describes the innovative nondestructive bridge deck inspection technology using high-definition infrared and visual imaging. This combination of instruments benefits from rapid and large-scale data acquisition capabilities. Depending on the target structure, different systems have been developed to combat on-site accessibility issues and long man-hours in the field associated with conventional sounding methods. FLIR hardware and proprietary software was integrated into a mobile system called the Deck Top Scanning System (DTSS). This system identifies thermal and visual variances indicative of deficient areas within concrete. By introducing advanced functions in automatic detection, image stitching, and geo-referencing, the system makes for practical and adaptable solutions to manage inspection data (Watase et al. 2015)).

The daily fluctuation of radiation into and out of the Earth's atmosphere has allowed structural inspectors to study thermal patterns within concrete, brick, and asphalt surfaces. The technology makes full use of this natural occurrence by conducting inspections during day and night. Infrared thermography (IRT) captures irregularities in these fluctuations generated by flaws such as cracking, spalling, or delamination of internal structural layers. Alongside a synchronized visual record, it can prove a very powerful tool for structural analysis. We strongly encourage the use of some form of visual technology alongside IRT, due to discoloration, oils, or other anomalous occurrences that can create false positives within IRT data. Given a visual technology with high enough resolution, it is possible and practical to conduct the visual inspection of cracks and spalling at the very same time.

Through its implementation in Japan over the course of two decades, the technology is opening new possibilities in a field with much untapped potential. In this paper, findings and lessons learned from our past experience in Virginia and Pennsylvania are described as examples of mobile NDE (DTSS) in action.

2 IMPLEMENTED TECHNOLOGY

The Deck Top Scanning System (DTSS) features an IRT camera and two line-scanning cameras (LSC). This equipment is mounted onto an inspection vehicle, from which the system can capture visual data during the daytime and IRT data during proper testing periods in either the morning or evening. As a result, the DTSS rules out the necessity of lane closures and direct visual inspection. This promotes safety and efficiency in the field by steeply reducing the time which workers and engineers are exposed to highway dangers on-site (Hiasa, Et al. 2016).

These instruments are accompanied by both IRT image processing and crack detection software, called Ir-BAS and JeEditor respectively. The software packages perform data collection, image correction (an orthographic representation of an image taken at an angle), image stitching (the forming of one composite image with many smaller images), GPS coordination assignment, automatic damage detection, and other analysis functions. The DTSS has classically been applied to concrete structures such as bridge decks and parking garages.

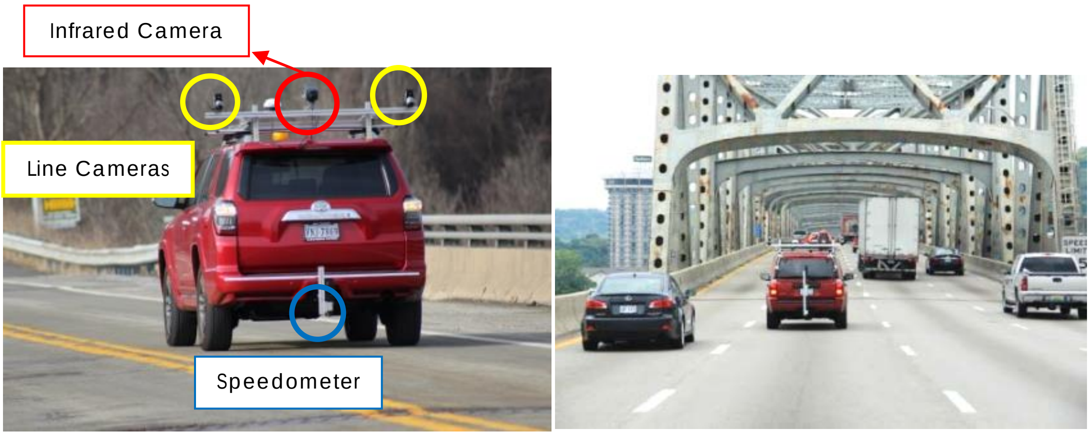

Figure 1. The Deck Top Scanning System (DTSS)

With the accumulation of data from repeat tests, controlled and uncontrolled, as well as first-hand experience on site, accurate monitoring of the progression of cracking, spalling, and delamination is possible. The technology is accurate enough to calculate the changes in length, width, and/or area of deficiencies over practical time periods (six months to a year, for example). Also, the nature of the resulting data contributes to a visual record of entire structural surfaces, which can be pragmatically saved and referred to in the future. With a comprehensive visual record of target structures, more predictive power in life cycle models and cost models will drive wiser future planning.

2.1 Infrared Thermography Technology, Automatic Detection, and Processing Software (Ir-BAS)

The recommended camera model for IRT scanning is the FLIR A6701sc model, capable of taking thermographs at high speeds due to its fast exposure rate and integration time (similar to the shutter time of a visual camera). It can also detect very finite differences in temperature (down to 0.1°C), making it possible to conduct inspections at night, when temperature differentials between sound and unsound regions tend to be quite slim.

The core of our infrared analysis technology is a software called Ir-BAS (which also includes the stitching software IrLay). It implements a comprehensive database comprised of past bridge inspection sites. The software translates infrared data into algorithmically sorted images, displaying points of potential delaminated areas in real time (as displayed in Figure 2 below). Conventionally, IRT images must be reviewed by an experienced technician during long hours of post-processing, but our program's auto-detection function offers a quicker alternative. It emphasizes thermal anomalies and pronounces large temperature variations within naturally occurring temperature gradients. This pronunciation may identify deficiencies which would be otherwise overlooked while reviewing large amounts of data.

Refer to Figure 2 and 3 below. Raw thermographic imagery can only display temperature readings as they are, incorporating a wide range of temperatures over a certain area. Doing so will unfortunately mask thermal anomalies, making them difficult to spot. IrBAS software detects gradients and effectively filters them, uncovering what lies in their midst. The software retains the original temperature data but makes it much easier on the viewer to pinpoint areas of interest.

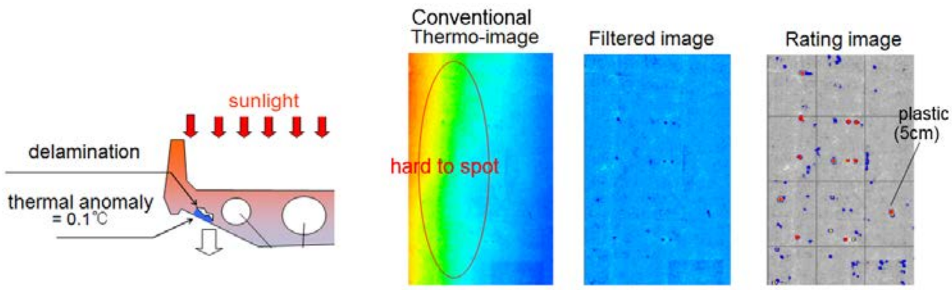

Figure 2. Thermal gradient filtering function

The extraction of the gradient is possible by retaining distribution temperatures other than the pattern made by the gradient and using them as a basis for producing an image which emphasizes temperature variation. Also, average temperature is determined in very small groups of pixels and used as a basis for the adjusted display. This process is portrayed graphically in Figure 3 below.

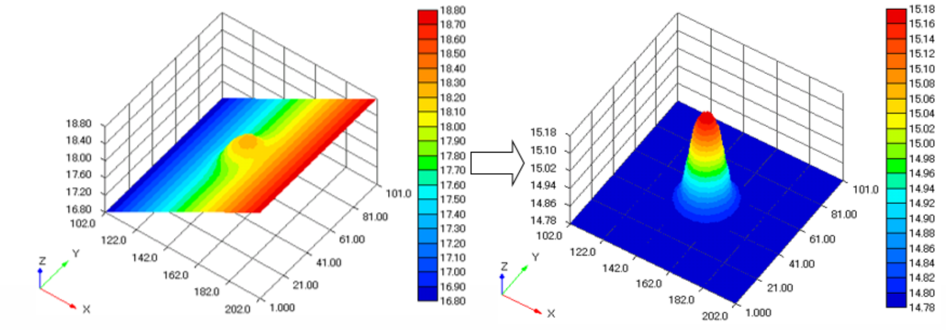

Figure 3. Effects of thermal gradient extraction (IRT image processing)

It is through this operation which unsound areas are discriminated from sound areas: by overhauling the IRT data itself and analyzing temperature differential in groups of pixels. An advanced numerical model, which can be adjusted within program settings, automatically picks out areas in which temperature differentials cross a certain threshold (Akashi et al. 2010). For example, in the left-hand graph in Figure 3 above, the temperature of the sample anomaly is around 18.4°C, whereas the temperature of the proximate sound area is around 17.90°C. By taking the average temperature around this anomaly and calculating the trend of the background temperature gradient, a new field (or scale) of temperature is produced, essentially neutralizing the gradient. The previous 0.4-0.5°C differential is therefore magnified in the right-hand graph. Depending on the IRT camera used, the minimum detectable differential may change, but the process within the software remains the same.

Ir-BAS is also responsible for image correction and stitching. Refer to Figure 4 below for a systematic diagram of workflow. GPS data taken on site is used to properly orient and place images, and the resulting string of images can either be viewed on a geolocated plot (which accurately maps the pathway and direction of the pass), or vertically (aligned in a straight line). With the stitched imagery, it is possible to export into a desired image file type and be compared side-by-side with the visual line camera scan.

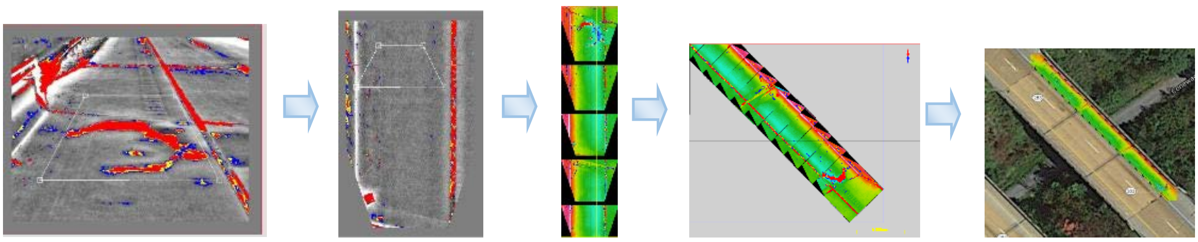

Figure 4. IRT image stitching process

2.2 Visual Proofing and Crack Detection with High-definition Line-cameras

The line-scanning camera (LSC) equipment is used to produce a high-quality visual diagram of bridge decks, and in turn a visual proof for the IRT data. Frequently, things such as discoloration, oil spills, or other markings can result in false detections when reviewing the IRT thermographs, so it is necessary to compare both visual and IRT data side-by-side (or by overlaying one on top of the other). Cracks down to a 0.3mm width can be recognized on the line scan, and generally these detections are measured and drawn manually onto the images by a trained engineer.

Each individual camera scans at a 13ft width (around 18ft in total, with 8ft overlapping), in a constant stream. The camera requires motion, ideally a steady speed to operate, but the frequency and spacing of recorded lines are adjusted in real-time by a high-performance speedometer. See more details about the LSC in the table below.

The line data is processed and analyzed with an image manipulation and crack editing software called JeEditor. Based on intervals determined by speedometer and GPS, the software arranges the visual line data (rows of ~10-100 x 4010 mm² pictures) and provides an interface which the user can overlay scaled gridlines and deficiencies. The deficiencies can be classified based on type, area, width, etc. Various light-correction functions allow the user to enhance the image and make hairline cracks easier to detect. Areas/lengths drawn in the interface are quantified, and can be output to excel for report composition.

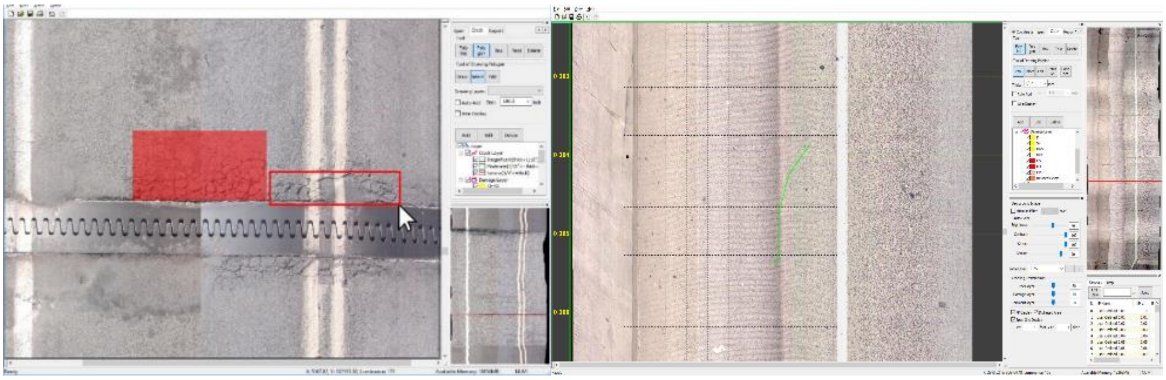

Figure 5. Image editing software interface

An LSC system is the recommended alternative to high resolution area-scanning photography or video, and exceeds ASTM D 4788-03 standards. In our experience, the DTSS using LSC and IRT in combination has provided higher resolution image results (resolution: 1mm²/pixel) in assessing and documenting defects, and does not result in blurring commonly observed in area-scanning cameras.

3 FIELD VALIDATION TEST

3.1 Project location

The project diagnosed the condition of a bridge deck on the Pencoyd Viaduct (I-76) approaching Philadelphia along the Schuylkill River. The project scope included deck top scanning for identification and quantification of delaminated or spalled areas. The data acquired was validated by sounding test during a lane closure which took place nearly two weeks after the initial scanning. The bridge in question is shown in Figure 6 below.

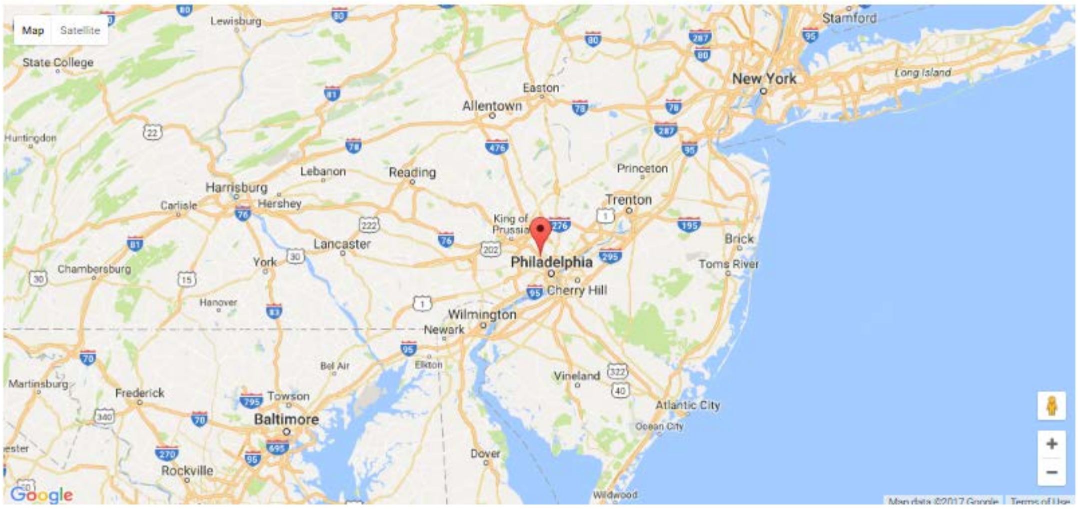

Figure 6. Pencoyd Viaduct in Philadelphia, PA

The field data collection for IR images was performed between 8 pm to 10 pm on April 18th, 2017 (Figure 7). Digital imagery was collected during daytime (between noon and 1 pm) on April 19th. The reason behind taking both a visual and an infrared scan is the necessity of visual proofing,or checking for false positives. While interpreting IR scanning results, it is important to differentiate and subsequently exclude false positives on the deck surface caused by things such as spilled paint, roadway striping, or other unusual objects. Without making this comparison, it is possible to misinterpret a discoloration as a delamination, because they tend to exhibit similar temperature differentials.

3.2 Field data collection

The total scanning hours in the field for digital imagery was approximately 50 minutes for both West bound and East bound bridges, including shoulders and two lanes. The nighttime IR scanning was conducted in the same manner in about 50 minutes. To ensure a successful scan with IR technology, it is critical to select the best time window for the field data collection, in respect to temperature conditions. The best and most stable time window generally occurs from the start of an intensive thermal flow from the concrete to the air at sunset,and lasts until the temperature differential between the concrete and air stabilize. Differentials and thermal anomalies can be detected at this time using an infrared camera with a high thermal sensitivity and fast exposure time. In general, this thermal flow is created by both ambient temperature and radiative cooling at night. Figures 8 and 9 below illustrate the behavior of temperature and radiation within concrete structures over the course of a day.

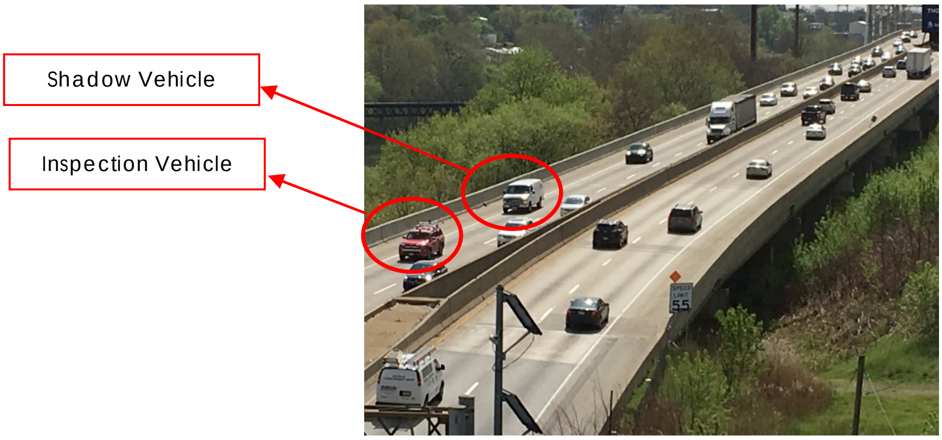

Figure 7: Digital image scanning

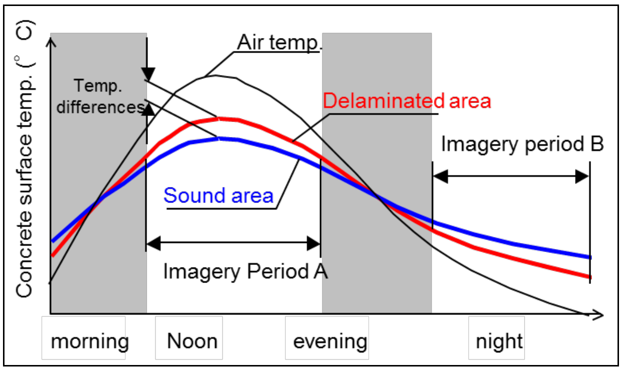

Figure 8. Ambient and concrete temperature variation a day

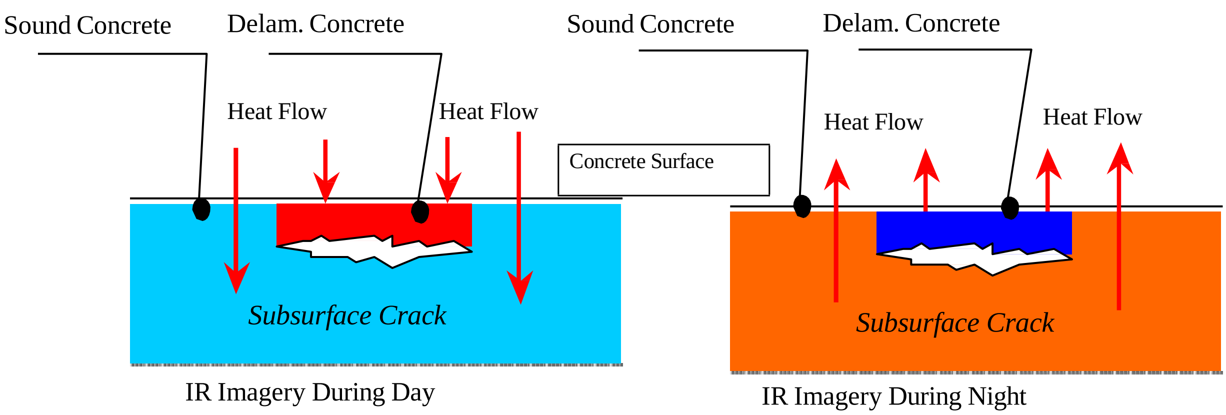

Figure 9. Thermal flow in concrete structures during day and night

A temperature record taken near the site is displayed in Figure 10. The temperature of ambient air (light blue) and a sample test piece concrete (red and green for unsound and sound concrete, respectively) was recorded at a parking lot near the inspection site. During the time of the IR scan (8 pm – 10 pm), approximately one-degree Celsius gap between sound and unsound concrete occurred.

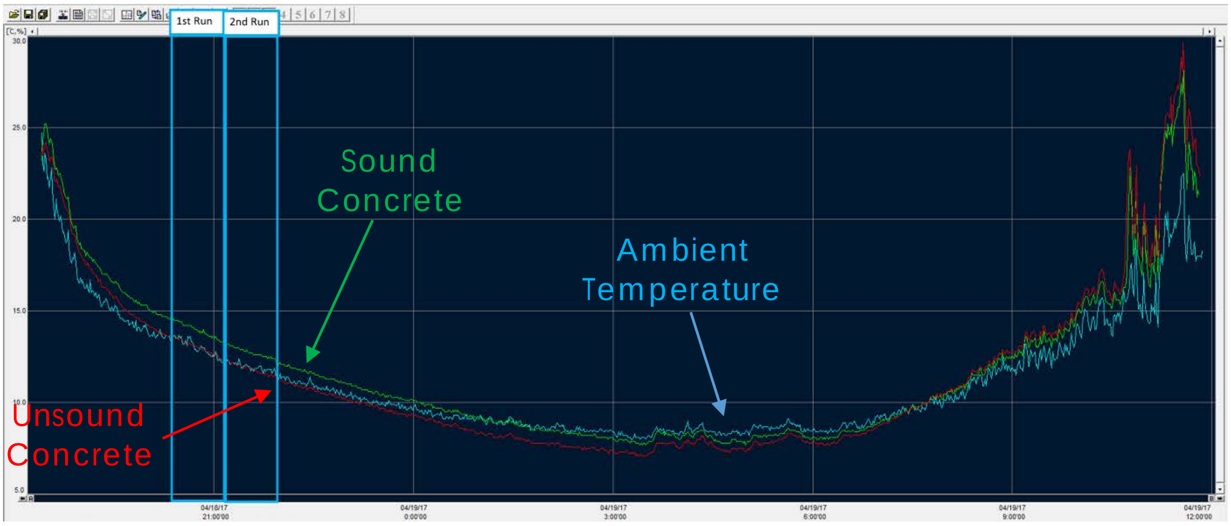

Figure 10: Temperature graph recorded on April 18 and April 19. IR scanning period is shown in blue box.

3.3 Findings from the high-speed scan

Favorable weather conditions and a smooth scan resulted in a successful analysis of the bridge. All data collected—raw infrared, processed infrared, and visual—were compared closely side-by-side to eliminate false positives. The AASHTO Manual for Bridge Element Inspection, First Edition (AASHTO, 2013) provides a guideline for condition state definition of bridge elements based on the severity of delamination, spalling, exposed rebar, and cracking conditions. For the East bound bridge, the element condition state (CS) for reinforced concrete decks (Element #12) was determined based on the mobile scanning results. Broadly, this bridge exhibited only slight signs of defects compared to the overall bridge roadway deck area - less than 2% of deck area with some delamination. The distribution and location of the AASHTO-categorized deficiencies for each bridge was also prepared in the form of a map, where the deficiencies were highlighted and super-imposed onto an image of the bridge decks. Percentage of deck areas for each condition state was also summarized for each span of the bridge and graphically displayed as shown in Figure 11. This information can be used by bridge owners as a general assessment, and can help to prioritize future repair/rehabilitation programs by identifying deficient areas in their early stages.

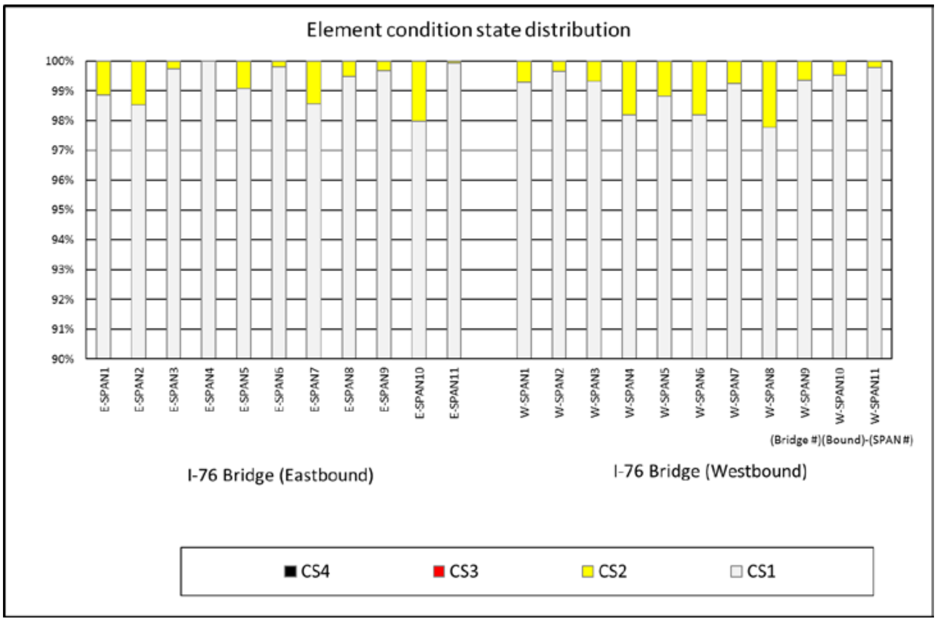

Figure 11. Condition state distribution for each span of the bridge

The result from the high-speed scanning was displayed on the deficiency map for details (see Figures 12 and 13 for examples). The tables in the deficiency map show the percentage of deck areas for each condition state. Two weeks later, the right lane and the shoulder of the East bound bridge were closed for visual inspection and sounding tests for validation purposes (Figure 14). Figure 15 is the validation results depicted on the deficiency map for the East bound bridge. The areas marked in orange color are detected as delamination by the sounding test. The areas in yellow color are detected as potentially delaminated by the high-speed infrared scan. We added GREEN dashed boxes if these orange and yellow areas were consistent (that means correct detection by infrared). However, some of the yellow areas were proved to be "false positive', and we added RED dashed boxes to these false positives. Generally speaking, the defective areas were successfully detected by the infrared with only two exceptions in Span 2 and Span 10. In these areas, a signature of delamination was found by the IR scan, but we interpreted these areas as false positive on the basis that exposed aggregate and a continuous discoloration on the middle of the deck surface camouflaged this area and it was challenging to distinguish this area from the other sound areas which showed a similar temperature distribution. Most of the false positives were also caused by the same reason.

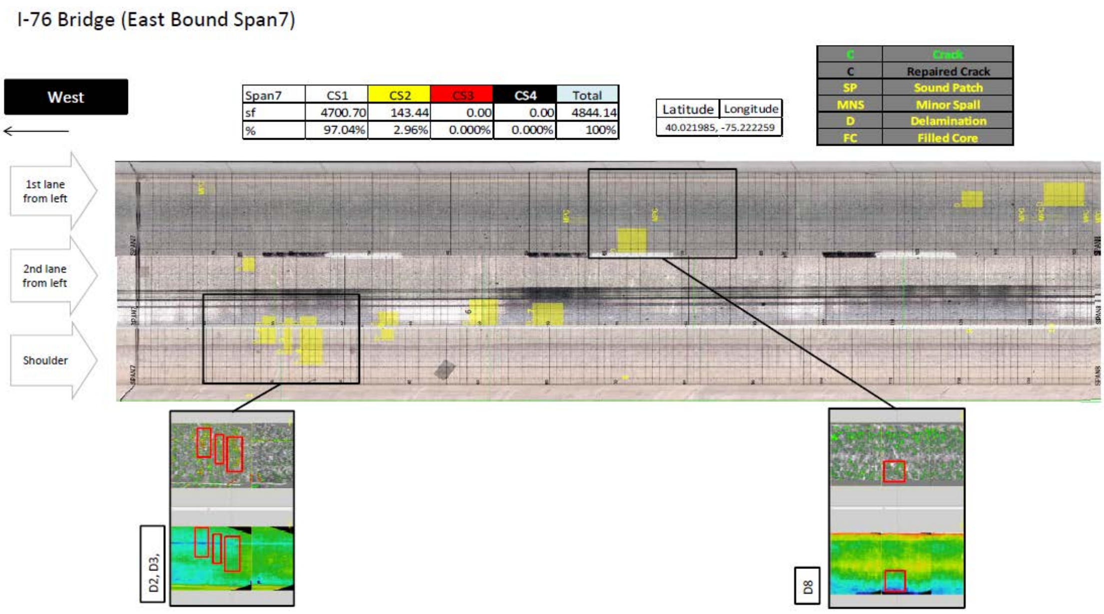

Figure 12: Deficiency map for Span 7 of the East bound bridge

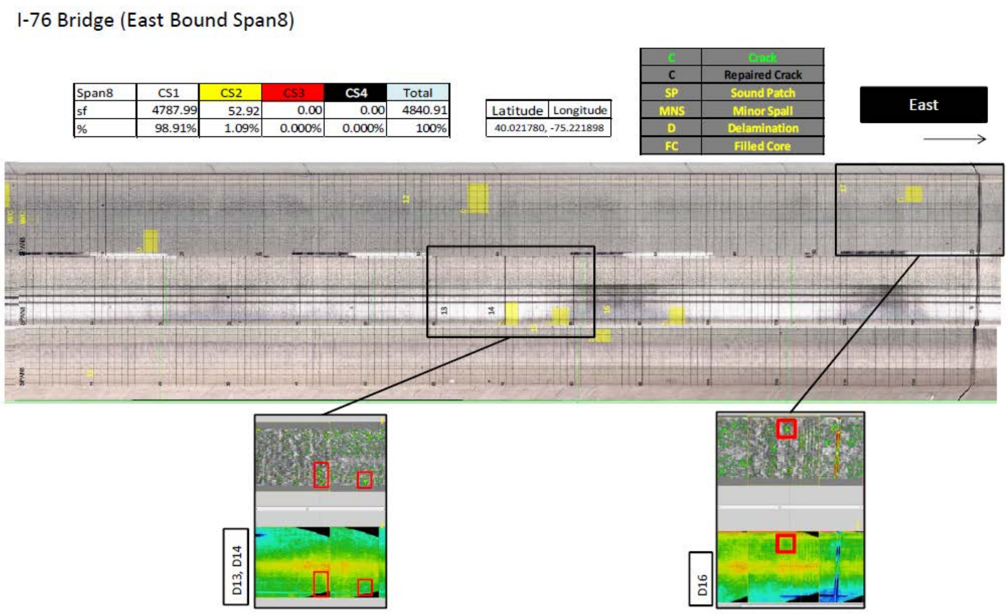

Figure 13: Deficiency map for Span 8 of the East bound bridge

Figure 14: Sounding probe used for the validation test

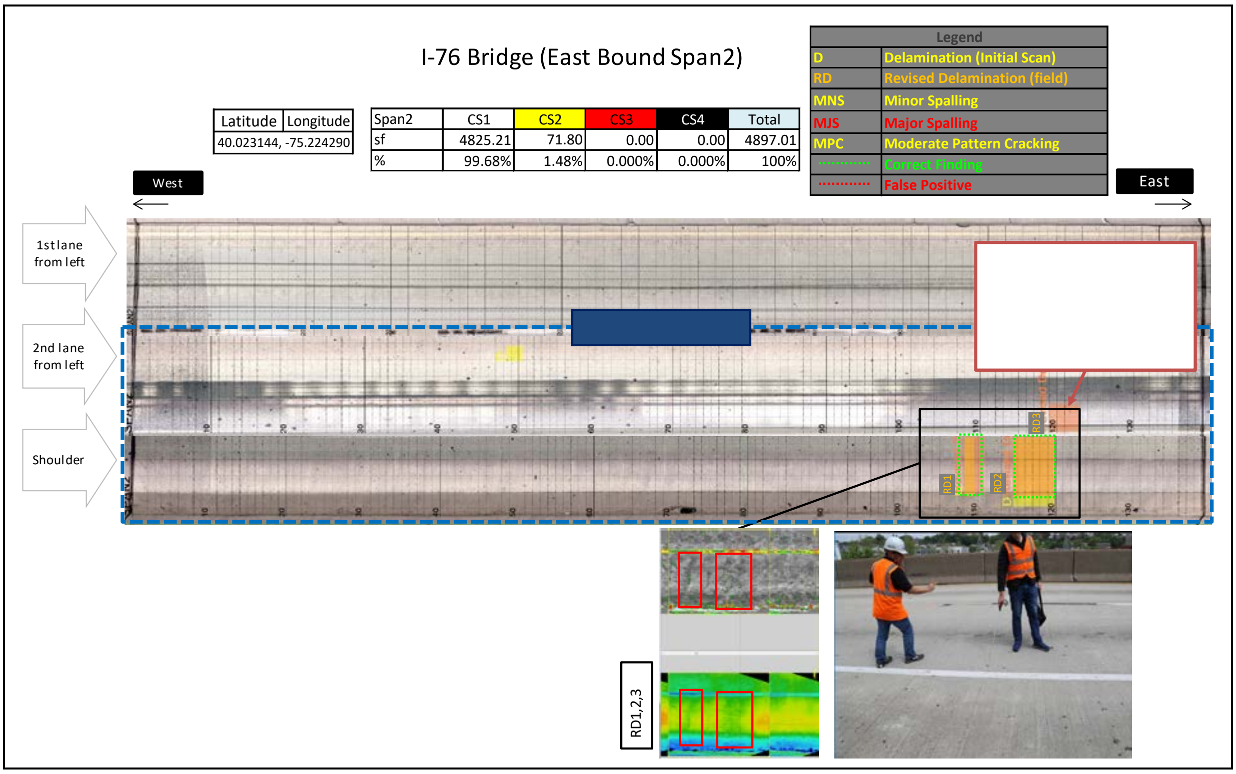

Figure 15: Deficiency map with validation results (Span 2, East bound)

3.4 Conclusions and recommendations

The result from the high-speed scanning for the concrete deck for the Pencoyd Viaduct was displayed on the deficiency maps, and will be further examined as the analysis of the viaduct continues in the coming year. The results were validated by the sounding test applied during lane closure, and provided an excellent opportunity to cross check our results, and heighten our knowledge of signatures of delamination. The sounding test proved that most of the defective areas were successfully detected by the infrared thermography technology. However, the exposed aggregate due to the abrasion of concrete made it challenging to distinguish the delaminated and sound area from the infrared results, causing some false detections. From the validation results, it can be concluded that high-speed infrared and digital image scanning can provide valuable information of current deck conditions with reasonable accuracy. The information provided for identification and mapping of deficiencies will serve as an invaluable reference for the purposes of future evaluation and comparison. The bridge owner can use the comprehensive deficiency map for monitoring distressed deck areas and planning future repairs, as well as summarizing AASHTO element level inspections in square footage or percentage of deck area. The deficiency map and element condition summary generated by the deck scanning technology can serve as a solution for more efficient, objective, and safer bridge inspections in comparison to traditional approaches, especially for relatively large-scale bridges with heavy traffic volume. To assure the reliability of IR data, it is recommended to select the best field data collection time periods and to use an IR camera equipped with a cooled detector. Using enhanced analytical tools, the engineer can pinpoint locations of deficiency, allowing more efficient inspection protocols, improved operational safety, all while driving lower life cycle costs for owners. Other non-destructive evaluation technologies and any hand-held scans can also be applied for more detailed condition assessment for the selected areas denoted by high-speed scanning technology. Combining the deferent type of NDTs depending on their data collection speed, accuracy and cost will provide better solutions for bridge owners to efficiently and properly monitor the bridge conditions, supporting data-driven (objective) decision making on bridge maintenance and management.

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