MDOT RC-1617B

**Project Title:**

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

## FINAL REPORT

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**16. Abstract**

This project piloted the findings from an initial research and development project pertaining to the detection, quantification, and visualization of bridge deck distresses through the use of remote sensing techniques, specifically combining optical and thermal imagery, and expanded by increasing the rate of data collection to near-highway speed (speeds of at least 45 mph). Specifically, six large deck bridges (>90,000 sf) were assessed, without closing lanes to traffic, and are presented. Top deck concrete surfaces were evaluated for spalls and delaminations, and were recapped in map-based and table-based element level summaries with percentage and area by condition state and by span. Personnel and computing times were documented, and costs were estimated for a similar future bridge deck condition assessment for a large deck bridge. Additionally, this pilot project conducted a 3-D Optical Bridge-evaluation System (3DOBS) accuracy assessment, and provided training and demonstration sessions to help MDOT personnel understand and implement these technologies.

By identifying element level condition states of concrete decks through innovative methods of data collection and advanced data processing, implementation of these combined remote sensing technologies has the potential to become a standard MDOT business practice.

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# Research Report Disclaimer

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## Executive Summary

Just over 30% of the U.S. transportation infrastructure has passed its expected service life (FHWA 2011). The new bridge construction rate has subsided in the past decades as the nation has changed to focus on infrastructure preservation. 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 led to a renewed interest in remote sensing. Remote sensing applications for bridge inspection is 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 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, deck condition assessment is necessary to ensure the integrity of the bridge structure.

The initial "Evaluation of Bridge Decks Using Non-Destructive Evaluation (NDE) at Near Highway Speeds for Effective Asset Management" research project incorporated multiple remote sensing techniques and systems to detect, quantify, and visualize bridge deck distress features (Ahlborn and Brooks, 2015). These techniques and systems include a 3-D Optical Bridge-evaluation System (3DOBS), passive thermography, and the Bridge Viewer Remote Camera System (BVRCS). During the initial phase of the project, 3DOBS was upgraded to include the RED Epic optical camera, allowing increases in the speed of the collection vehicle and in resolution of output imagery. The RED Epic allowed 3DOBS to operate at speeds up to 45 mph over bridge decks with imagery resolution similar to that of the lower speed original prototype. Passive thermography allowed the project team to detect and quantify potential delaminations within the bridge deck. BVRCS demonstrated the use of a low cost deployable system that provides location-tagged visual analysis of bridge deck conditions, which can occur during an active bridge inspection, creating an up-to-date photo inventory of a bridge deck and distress features.

For the project's second phase, the three systems were combined onto a single vehicle for bridge condition assessment. A new vehicle mount was developed which holds both 3DOBS and thermal imaging equipment. This enabled simultaneous vehicle collection of optical and thermal imagery at near-highway speed. A Trimble global positioning system (GPS) antenna was also attached to the mount so the imagery can be referenced to the same location in a geographic information system (GIS). The GPS data is also used for the referencing of BVRCS data by using the GPS track log. As imagery from each system is processed, it is similarly referenced and can easily be displayed together in a GIS. Through the processing and analysis of each system's imagery, the project team demonstrated that remote sensing technologies have the potential to enable MDOT to assess bridge deck condition without the need to close traffic lanes. MDOT Bridge Management team members, including inspectors and bridge managers, are logical consumers of the bridge condition data derived from the optical and thermal data sources, as the percent spalled and percent delaminated areas for bridge deck surfaces are information that is

recorded in current bridge inspections. Data collected with these technologies can be used to assess bridge deck National Bridge Inventory (NBI) and deck surface element condition ratings while at the same time keeping inspectors safe and creating repeatable and objective results.

This pilot project phase built upon the findings of the initial project pertaining to the detection, quantification, and visualization of bridge deck distresses through the use of remote sensing techniques, and expanded by increasing the rate of data collection to near-highway speed (speeds of at least 45 mph). Six large deck bridges (>90,000 sf) were assessed and are presented. Additionally, this pilot project provided training and demonstration sessions to help MDOT personnel understand and implement these technologies.

**Condition Assessment of the Top Surface of Concrete Bridge Decks**

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

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. Passive thermal imaging and 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. In addition, the BVRCS, also an optical system using GoPro cameras with GPS location tagging, was developed to provide a high-resolution photo inventory of the top deck surface while travelling at highway speed.

Multiple field deployments of the non-destructive testing methods at six MDOT big bridges were conducted in Fall 2015 and Winter 2016. At each bridge, 3DOBS, passive thermal infrared camera, and BVRCS collected data in unison as the thermal imaging data collection vehicle (operated by GS Infrastructure, Inc.) drove across each lane of the bridge. Data collected via each system were processed and analyzed to produce six layers of georeferenced datasets and is available for decision support. The layers include an orthoimage, digital elevation model (DEM), Hillshade of DEM, thermal mosaic, detected spalls, and potential delaminations. Due to processing complications of data collected from bridge decks in very good to excellent condition, the DEM and Hillshade of some bridges were not completely mapped, but representative data products from some parts of the bridges are included in this report. A combination of these layers will enable MDOT to perform a change detection analysis on the distresses and provide objective data to assist in generating condition state assessments and NBI ratings for the top surface of the concrete bridge deck.

For the six large deck bridges and the 3DOBS accuracy assessment bridge, top deck surface evaluations for spalls and delaminations are recapped in table-based and map-based element level summaries with percentage and area by NBI Condition State and by span. US-131 NB in the Grand Region is depicted below in both formats (Table 1 and Figure 1). In addition, Figure 2 illustrates the individual delamination and spall locations on the top deck surface by element level condition state ratings.

**Table 1: Area of condition state per span for the US-131 northbound bridge deck.**

| Location: US131 | Area of Span ($ft^2$) | Area Cond. State 1 ($ft^2$) GOOD | Area Cond. State 2 ($ft^2$) FAIR | Area Cond. State 3 ($ft^2$) POOR | Area Cond. State 4 ($ft^2$) SEVERE |
|---|---|---|---|---|---|
| Span 1 | 7,642 | 7,629 | 13 | 0 | 0 |
| Span 2 | 9,318 | 9,299 | 19 | 0 | 0 |
| Span 3 | 15,456 | 15,451 | 5 | 0 | 0 |
| Span 4 | 14,872 | 14,865 | 7 | 0 | 0 |
| Span 5 | 15,120 | 15,105 | 15 | 0 | 0 |
| Span 6 | 13,711 | 13,675 | 36 | 0 | 0 |
| Span 7 | 15,524 | 15,489 | 35 | 0 | 0 |
| Span 8 | 12,647 | 12,643 | 4 | 0 | 0 |
| Span 9 | 11,635 | 11,601 | 34 | 0 | 0 |
| **Total** | **115,926** | **115,757 (99.85%)** | **168 (0.15%)** | **0 (0%)** | **0 (0%)** |

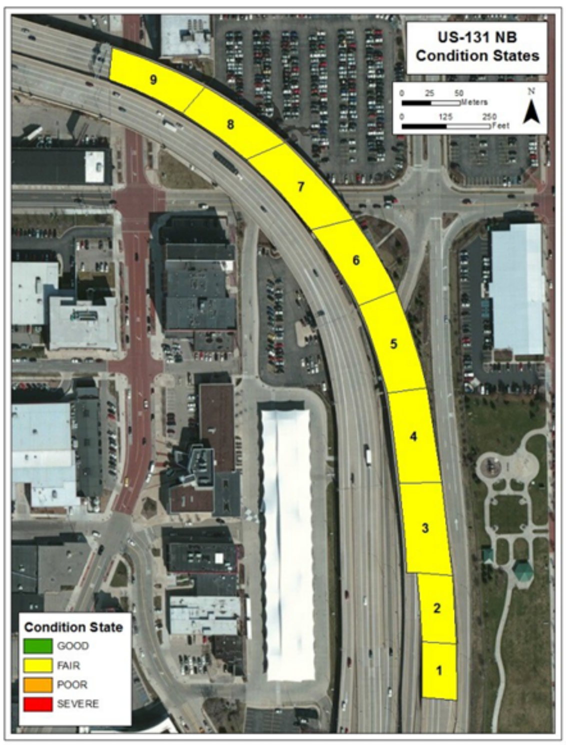


**Figure 1: Summary of condition state per span at US-131 northbound.**

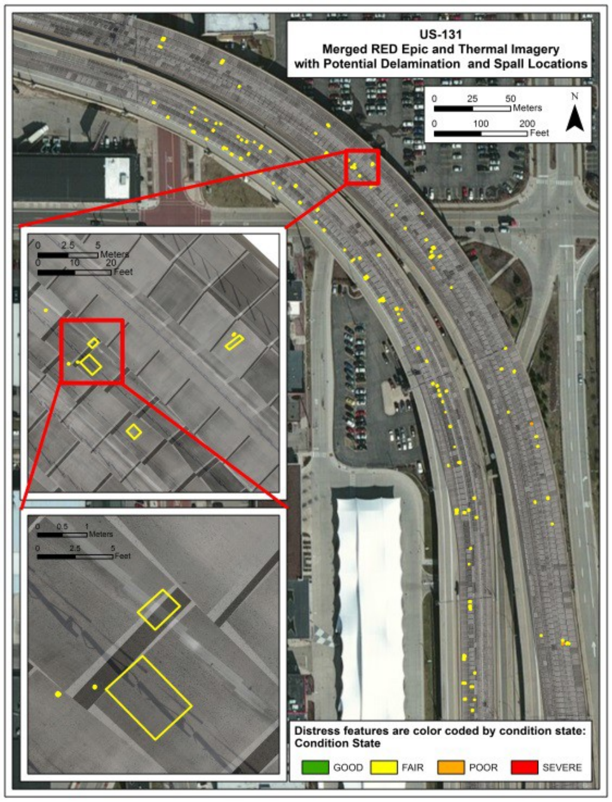


**Figure 2: Location of potential delaminations and spalls on US-131 northbound and southbound bridge decks.**

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. 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 will most likely be accessed for use prior to the next inspection or during preliminary bridge scoping.

## Estimate of Time and Costs for Future Large Deck Bridges

Data collection and processing times were recorded for all three technologies and the six large deck bridges studied. Collection time on the bridge decks in the field averaged 1.2 hours, including a delay due to a traffic accident. When excluding the bridge with the delay, collection time averaged less than one hour.

For the bridges analyzed under this project, the total personnel time to process 3DOBS data averaged 12.7 hours per bridge, with a range of times between 9.7 and 19.7 hours, whereas the processing time for BVRCS data averaged 45 minutes albeit that time is expected to reduce to 25-30 minutes as the operator efficiency increases. Data processing time for infrared thermography averaged 23.1 hours per large deck bridge, ranging from 19.5-27 hours. A more detailed breakdown of data collection and processing times can be found in Table 23.

An estimate of total personnel time and cost required to conduct this type of inspection on a bridge similar to those studied in this project was based on a representative scenario of a six lane, 1500 ft long concrete bridge deck. Based on the findings of this analysis, it was determined that a total of 51.65 personnel hours would be required for equipment setup, data collection, data processing, data analysis, quality assurance, and reporting. Using a cost rate of $60 per hour, the total cost estimate is $3100 for this large deck bridge. A detailed breakdown of this estimate can be found in Table 24 and does not include the cost of equipment, travel to and from the site, computing time costs, or other associated fees. Data storage needs were also estimated for each technology for this representative scenario (Table 26) and ranged from 2.84 to 32.4 GB.

**Training and Demonstration Activities**

With an objective of gaining an understanding of the field readiness and demand for advanced technologies by current bridge inspectors, a general training and demonstration session was conducted in January of 2016 to provide a real-time data collection and processing demonstration of 3DOBS and BVRCS. Attendees, including inspectors, regional bridge engineers and photogrammetry survey experts, were also provided with a brief overview of other MDOT-funded research projects taking place at the Michigan Tech Research Institute (MTRI). Project progress and further questions or concerns were addressed before the conclusion of the meeting.

# 1. Introduction

Through previous research conducted by the project team, it has been determined that remote sensing technologies have the potential to allow MDOT to assess bridge deck condition without the need to close traffic lanes and to limit the time that inspectors are exposed to dangerous environments. Research performed by the team under the original project (OR10-043) has shown that combining thermal and optical imaging data collected at near-highway speed can provide a detailed assessment of delaminations, spalls and cracking of the top surface of a concrete bridge deck. Optical imagery has also provided a detailed up-to-date photo inventory of the deck. Results from previous research has been presented to MDOT Bridge Management team members and include data derived digital outputs from the optical and thermal data sources such as an overall percent delaminated and percent spalled areas of the bridge deck (MDOT RC-1617, Ahlborn and Brooks, 2015). These types of spatial and quantitative information are necessary for MDOT to assign condition state ratings for element level inspections and the entire bridge deck.

The OR10-043 Implementation Action Plan included in MDOT Report RC-1617 recommended that remote sensing technologies, such as these optical and thermal options, be integrated into the bridge inspection program to enhance inspection of the top surface of concrete bridge decks. It was further recommended that MDOT conduct a pilot study to demonstrate the usability and productivity of the system with combined technologies. Subsequent discussions with the MDOT Research Advisory Panel (RAP) identified large deck bridges as the primary category to benefit most from near-highway speed inspections. By identifying element level condition states of concrete decks through innovative methods of data collection and advanced data processing, implementation of these combined remote sensing technologies has the potential to become a standard MDOT business practice.

This pilot project addressed the implementation of combining thermal infrared thermography (a service provided by GS Infrastructure, Inc.) with 3-D optical imaging (using 3DOBS) at near highway speeds for a series of MDOT-owned bridges with large decks. MDOT has conducted a detailed assessment of thermal imaging accuracy and repeatability (with others), yet there is limited assessment of this level for the 3DOBS optical imaging technology. Therefore, this pilot project also included a detailed 3DOBS accuracy assessment conducted on a MDOT bridge deck in Lapeer, Michigan. Additionally, the BVRCS, a low cost deployable system using GoPro cameras, provided visual analysis of bridge deck condition through a high- resolution geo-tagged photo inventory.

## *1.1 Background*

### 1.1.1 Objectives

This research was conducted to:

**Objective 1:** Demonstrate the capabilities of combined thermal and optical imaging at near highway speeds for condition assessment of large deck bridges.

**Objective 2:** Demonstrate the accuracy of 3DOBS optical imaging for assessment of spalls and cracking on bridge decks.

### 1.1.2 Scope

To accomplish the objectives, the research team expanded upon the results and conclusions from the initial “Evaluation of Bridge Decks Using Non-Destructive Evaluation (NDE) at Near Highway Speeds for Effective Asset Management” project (Ahlborn and Brooks, 2015), specifically concerning the 3DOBS, passive infrared thermography, and BVRCS technologies. The three technologies were combined together and used in unison during field data collection in Fall 2015 and Winter 2016. The previous updated 3DOBS system was once again deployed to evaluate the top surface of concrete bridge decks at near highway speeds; speeds up to 45 mph. The RED Epic was again chosen for near highway speed data collection due to its ability to collect 13.8 MP imagery at up to 60 frames per second (fps) using a “5K” video imaging sensor. Imagery from the RED Epic was processed in Agisoft PhotoScan, and can be processed through a spall detection algorithm. The RED Epic allows for higher speed at moderate resolution (as compared to the Nikon D800 in the previous project (Ahlborn and Brooks, 2015), which only allowed for higher resolution of crack detection at slower speeds).

Passive thermography was used to locate suspected delaminations and is capable of operating at highway speed. GS Infrastructure, Inc. (formally BridgeGuard, Inc.) has in-depth experience in using passive thermography at near-highway speeds to detect potential delaminations on multiple bridges across the country. Passive thermal imaging and 3DOBS camera sensors were combined side-by-side on the same data collection vehicle to detect spalls and delaminations on the top deck surface at near-highway speeds with a single pass per lane. Both optical and thermal datasets were referenced to the same coordinates and viewed in a GIS such as ArcMap. The goal of this research was to produce separate GIS data layers generated from the collected imagery, including an orthoimage, DEM, Hillshade of the DEM, thermal mosaic, detected spalls layer, and potential delaminations layer. A combination of these layers would enable MDOT to perform change detection analysis on the distresses and provide objective data to help generate NBI ratings for the bridge deck. In addition, the BVRCS, also an optical system using Go-Pro cameras, was again included in this analysis to provide a high- resolution geo-tagged photo inventory of the top deck surface while travelling at highway speed.

Training, including equipment overview, live data collection demonstrations, and data processing was provided for MDOT personnel. This session was conducted to help MDOT understand data fusion and processing such that MDOT can begin implementation.

Combining remote sensing technologies for NDE bridge inspections results in a suite of tools that represent 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. Review of Previous Research

Previous research conducted for MDOT by the project team focused on the evaluation of bridge decks through the use of non-destructive evaluation techniques at near highway speeds for effective asset management. For the analysis, remote sensing technologies were implemented in bridge deck surface and subsurface condition assessments of concrete decks, as well as concept testing for the assessment of the underside of the bridge deck. To detect spalls or cracks on the bridge deck, 3-D photogrammetry, or “the science or art of deducing the physical dimensions of objects from measurements on photographs of the object,” remote sensing techniques were incorporated in the analysis (Henriksen, 1994). Specifically, close range photogrammetry of the bridge deck (imagery taken less than 100 m (328 ft)) was used to generate 3D models of the bridge decks, from which condition information can further be extracted. 3DOBS collected high-resolution imagery from a vehicle as it was driven across a bridge deck. The high-resolution imagery is then reconstructed into a 3-D representation of the bridge deck and DEM, in which measurements of distress features such a spalls can be identified and quantified. Additionally, four of the six GIS layers (orthoimage, DEM, Hillshade, and spalls) related to bridge deck conditions were created through the use of photogrammetry and 3DOBS data (Figure 3).

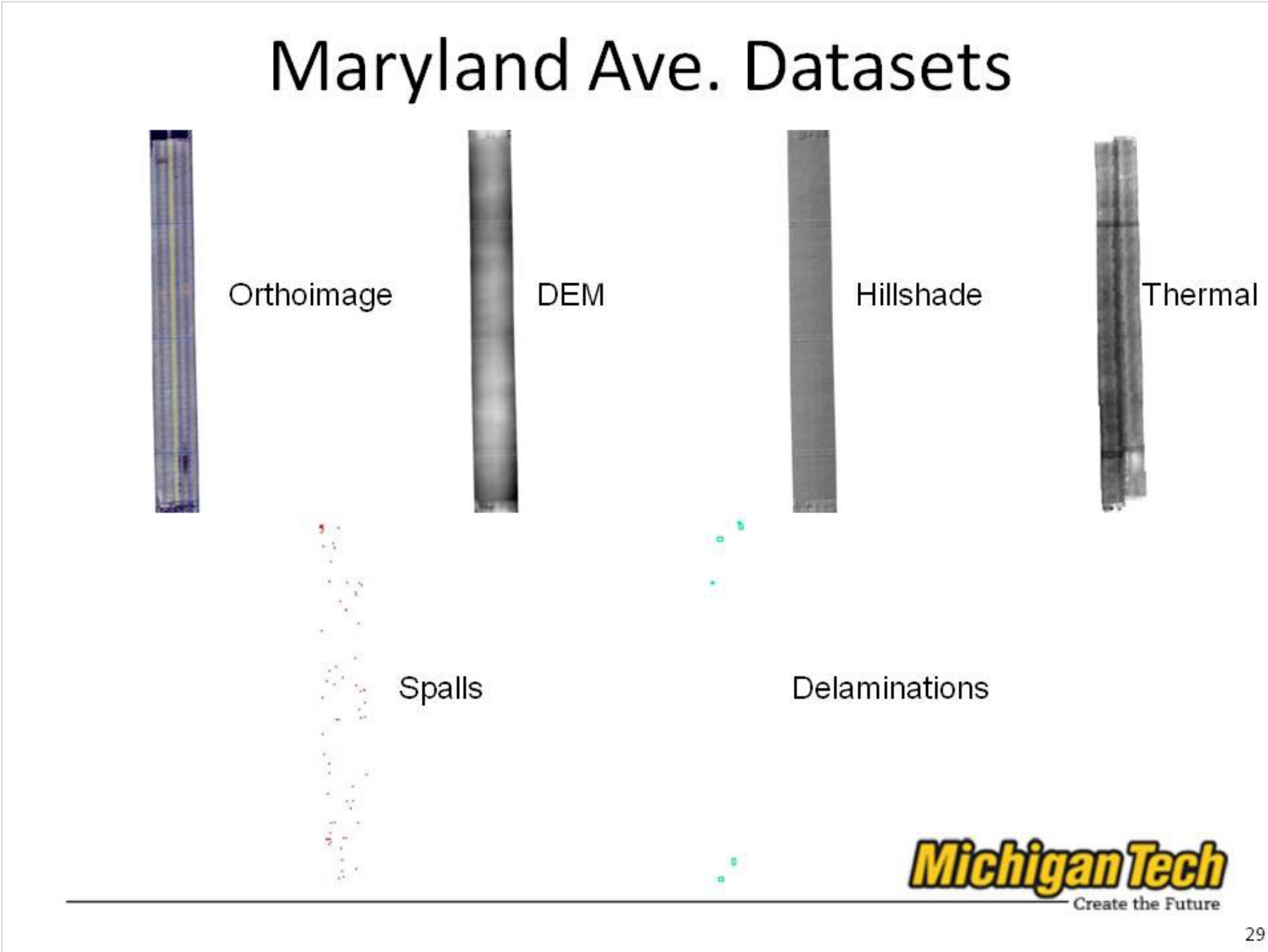


**Figure 3: GIS layers created from 3-D photogrammetry and thermography.**

Another remote sensing technology, passive thermography, was included in the analysis to detect delaminations within the bridge deck. Based on collecting radiant surface temperature data then converting the data into temperature measurements and a visual image, passive thermal infrared technology depends on the natural radiation of heat due to an object's internal heating system or property. Therefore, in the passive thermography assessment of the bridge deck surface, no external heating sources were used to heat the deck surface. Anomalies and subsurface delaminations interrupt the heat transfer through the concrete and appear to have different temperatures in thermal infrared imagery as compared to its surroundings sound concrete. Delaminations within the concrete resist heat transfer and warm up at a faster rate, therefore appearing warmer than the sound concrete. For this analysis, passive thermography allowed the project team to spatially determine where potential delaminations existed within the bridge deck, resulting in quantitative measurements such as the overall percent delaminations to be computed (Figure 4).

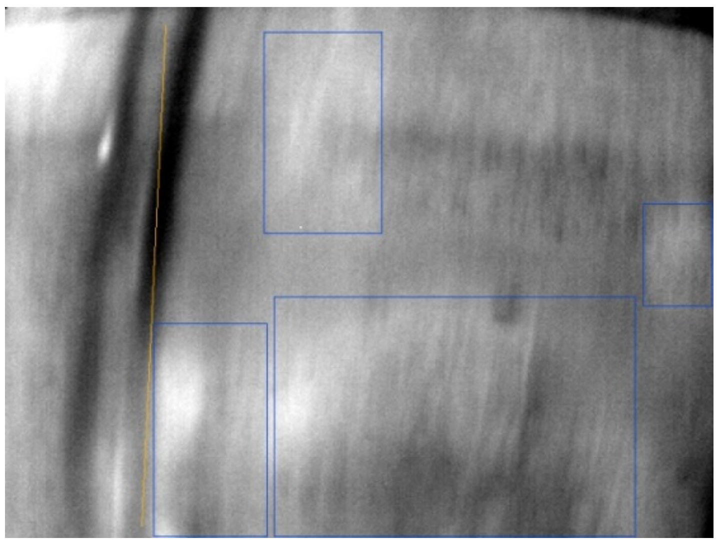

**Figure 4: Passive thermal imagery was processed and analyzed for the detection of potential delaminations (blue boxes).**

The Bridge Viewer Remote Camera System (BVRCS) consists of two cameras attached to the hood of the data collection vehicle and is used to collect high-resolution imagery of the bridge deck as the vehicle crosses the bridge. The photo inventory of the bridge deck can be used to provide an idea into the condition of the bridge deck, especially to analysts that were not present during data collection. Additionally, each image in the photo inventory is geo-located on the bridge deck using GPS data that is simultaneously collected during the data collection process through use of a track log. This offers an active link to be set up in GIS software such as ESRI Desktop ArcGIS that allows analysts to visualize the bridge deck at defined points (Figure 5).


**Figure 5: BVRCS imagery is displayed in GIS software.**

# 3. Methodology

## *3.1 Equipment*

### 3.1.1 3DOBS

The near highway speed version of 3DOBS is based around the RED Epic camera body (Figure 6). The total system cost about $25,000, which includes the camera body, lens mount, batteries and charger, Solid State Hard Drives (SSDs), and mounting equipment. The RED Epic captures 13.8 MP (5K video) frames at a rate of up to 60 fps. Data collection at a vehicle speed of 45 mph requires a frame rate of 48 fps to achieve the necessary imagery overlap.


**Figure 6: RED Epic camera body.**

A Trimble GPS was used to collect a track log of the data collection. The GPS receiver was mounted above the RED Epic so that the positions could be correlated. The Trimble has an accuracy of better than 10 cm. Prior to a data collection, a short few second video was taken of the GPS screen displaying the GPS time to correlate the GPS time with the camera time. During the geotagging process, the time difference was used to match the GPS positions to the corresponding video frame.

For data collections, the camera was mounted to the van using a pole mount and elevated to 9 ft above the road surface. The horizontal field of view at this height was 14 ft, which is enough to cover one lane per pass. During the data collections for the pilot study, each lane was driven twice to complete two "passes". With concerns that the bridge decks might be too flat and difficult to reconstruct, the center of the camera field of view (FOV) was over the right and left side of each lane. The additional overlapping imagery assists with the alignment of the frames and 3D reconstruction within Agisoft software.

To process imagery into a 3D model, there are three main steps. First, the individual video frames have to be extracted. The RED Epic camera is a video camera that can shoot at high frame rates. For our collections, a frame rate of 48 fps is sufficient to have a single point on the ground covered by at least 5 frames, which are necessary for 3D reconstruction. Adobe Premiere was used to perform frame extraction. Premiere was not able to extract frames shot at 48 fps but was able to export 50 fps. This leads to the addition of a duplicate frame being created of every 25th frame.

The second step is to geotag the extracted frames. Three scripts were written to assist with the automation of this step. The first script interpolated additional GPS points from the Trimble data. The RED imagery collects data at a rate of 48 fps and the Trimble is collecting once every second. The additional 47 points were equally spaced in between each of the Trimble points. This assumes that a change in vehicle speed between the one second intervals falls within the error of the Trimble unit and would not reduce the accuracy of the reconstruction. Prior to the geotagging of the frames, a second script deletes the duplicate frame so that each point in the expanded GPS data corresponds to a specific frame. The final script adds the latitude and longitude information from the GPS points into the exchangeable image file format (EXIF) data of each frame so data can be processed in close-range photogrammetric software.

Once the frames are geotagged, the final step is to process them through Agisoft PhotoScan Pro. The user has to manually enter in the lens focal length used during the collection and the pixel size in millimeters to ensure a proper reconstruction. This information is normally not needed for traditional still frame cameras because it is already stored in the photos exchangeable image file format (EXIF) data. Extracted video frames are stripped of EXIF data and therefore must be entered into the "Camera Calibration" dialog.

Most of the 3D processing is automated but the user must manually start each of the three processing steps. The first is image alignment, which calculates the camera positions and scene geometry and generates a sparse point cloud. The second step densifies the sparse point cloud and can produce a model up to the resolution of the input imagery. All of the models created for the pilot study used the "Medium" setting for this step, which produces a model at roughly half the resolution of the input imagery. This was done to shorten the processing time as it could take about two days to process a single large deck bridge through this step using the highest reconstruction setting using the processing workstations at MTRI. Cloud-based processing can shorten this time significantly.

The final step in Agisoft is to generate a mesh. In the previous steps, Agisoft creates a 3D point cloud. A surface is needed for the generation of a DEM. The mesh represents the bridge deck as it is a surface based on the 3D point cloud. Once a mesh is generated, a DEM and orthoimage can be exported. The exported orthoimage has the same resolution as the imagery used to create it. There are a couple of options for point cloud densification, which determines the maximum resolution of the DEM. The highest reconstruction setting will result in a DEM with the same resolution as the orthoimage, but this take a significantly longer processing time.

An example of processing time difference between the “Ultra High” (at the input imagery resolution) and “Medium” setting in Agisoft PhotoScan was done with 26 RED Epic frames. When processing the 3D point cloud using the medium setting, the processing time for the point cloud densification step was 10.3 minutes. By comparison the ultra-high setting took 8.9 hours to complete. Processing using the ultra-high setting takes approximately 52 times longer than the medium setting. The difference in resolution is 3.2mm for the medium setting and 0.8mm for the ultra-high setting. For a compromise between processing time and resolution, the medium setting is selected.

All three output datasets from 3DOBS are useful in the analysis of the bridge deck. The orthoimage allows the inspector to have a high resolution reference image of the deck. Furthermore, the orthoimage can also be used to locate and manually digitize features on the bridge deck such as patches or cracks large enough to be resolved in the imagery. The DEM is used for the analysis of spalling. Since the DEM represents the 3D point cloud, it allows for the spall area, depth, and volume to be calculated in a GIS. A hillshade is a 3D representation of the DEM which makes it easier to view features on the bridge deck. This is useful when showing the severity of the spalling for reporting and documentation.

### 3.1.2 Passive Infrared Thermography

Through the initial project, GS Infrastructure, Inc. resolved challenges relating to integrating passive thermal infrared data collection alongside and concurrent with 3DOBS. Specifically, GS Infrastructure, Inc. data became compatible with GIS software frameworks, allowing identified potential spalling features to be located, mapped, and quantified in relation to the bridge deck and spans. The stand-alone tools developed in the initial project mined the GS Infrastructure collection and analysis files, and created a specifically formatted output file outlining all potential delaminations on each of the large deck bridges studied.

The data collections were carried out using the 3DOBS / GS Infrastructure, Inc. thermal infrared camera vehicle-mount imaging system and high-definition digital imager to record visible and invisible defect data on the bridge deck. Data was collected one lane at a time at near- highway speeds until the entire deck had been scanned, and the recorded imagery was saved using proprietary software to a laptop computer. Upon returning from fieldwork, the thermal data was manually analyzed with the results imported into a CAD (Figure 7).

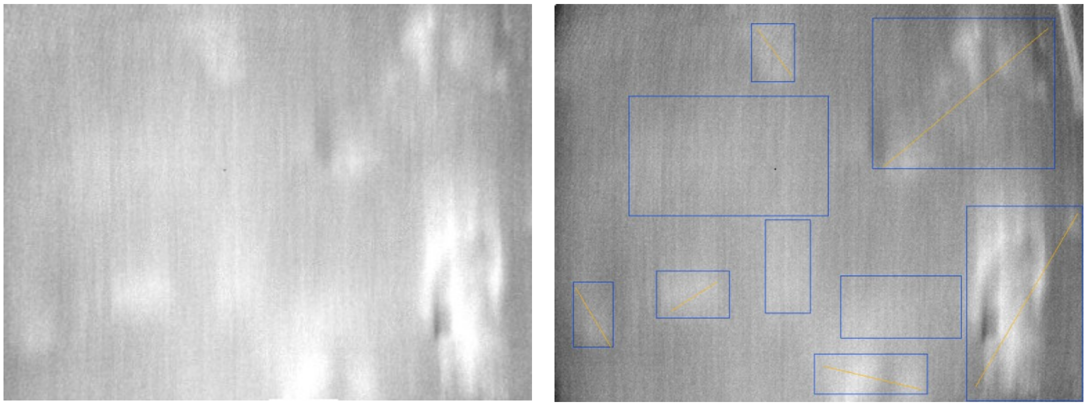

**Figure 7: Raw thermal imagery (left) and thermal imagery processed to highlight areas of potential delamination (right).**

The raw thermal imagery is also mosaicked to create a thermal mosaic of the entire bridge deck. This is done through a combination of manual and automated processes. First, the frames are processed through Adobe Photoshop to correct for lens distortion and for the camera tilt that is mostly automated. This step is needed to remove the “fisheye” effect caused by using a wide-angle lens. This can be seen in the frames in Figure 5. The frames are then processed through a script, which mosaics frames from a single pass. Each mosaicked pass is then manually georeferenced to the orthoimage of the bridge deck which was generated from 3DOBS imagery. This enables overlaying of the mosaicked thermal imagery on top of the orthoimage in GIS software, making data comparison and analysis easier.

Potential delaminations identified by GS Infrastructure, Inc. are marked as boxes on the thermal imagery. These frames are corrected for distortion and referenced to the thermal mosaic layer. An analyst then digitizes the potential delaminations in ArcGIS to create a shapefile, which can be layered with the spalls shapefile. The shapefile projection can be set to any standard required (such as “Michigan Georef” or the locally appropriate State Plane zone).

### 3.1.3 Bridge Viewer Remote Camera System

BVRCS is a low cost (less than $1,000) deployable system that provides visual analysis of bridge deck conditions as a vehicle is driven across the bridge deck. Consisting of two GoPro Hero 3 cameras, which are mounted to the hood on opposite sides of the vehicle, and images, are collected at a rate of one image per every half-second (Figure 8). The only exception to this method occurred at the I-696 bridge deck collection, where one GoPro Hero 3 camera was not operating due to a low battery. The rate of image collection (2 fps) provided a good overview of the condition of the bridge deck, without missing larger sections of the bridge deck due to vehicle speed, proving especially useful for a vehicle traveling near highway speeds (~45-50 mph).

**Figure 8: The two GoPro Hero 3 cameras set up on the data collection vehicle hood.**

During each data collection, the GoPros were capturing 12.3 MP images, corresponding to a file image size of approximately 4 MB per image. For each lane pass over the respective bridge, approximately 55 to 90 images were collected, corresponding to approximately 700 to 1,100 pictures per bridge (total values are dependent on the length and width of the bridge). As part of the BVRCS data collection, GPS data is collected in unison (at one data point per second) with imagery collection. It is especially important that each GoPro Hero 3 camera captures a picture of the GPS receiver's date and time, as that information allows for the correct time difference between the camera and the GPS to be specified for geotagging purposes. The GPS can be a high end Trimble unit with sub-decimeter accuracy, a Garmin field unit, or other similar system depending on image location geopositioning needs. The images are post-processed and locations are interpolated to the bridge deck based on the time adjustment calculated in GeoJot+ (http://www.geospatialexperts.com/GeoJot/), GeoJot+ which is available for an annual fee of $150. Free geotagging tools such as the one built in to Desktop ArcGIS can also be used, but the GeoJot+ process is very user friendly. After determining the time difference between the GoPro Hero3 camera and GPS receiver, each photo is georeferenced with the latitude, longitude, date, time, and image name placed on the image (Figure 9)


**Figure 9: Image collected by the GoPro Hero3 camera (left) and the GeoJot+ processed geotagged image (right).**

After each image is processed through GeoJot+, a ESRI shapefile is created with the approximate position of each image based on the GPS data. The shapefile's projection can be set to whatever the end user requires. The shapefile is then placed into ESRI's ArcMap software, with minor manual edits being required to separate the images since the GoPro Hero3 collected imagery at a rate of two per second as compared to the GPS data, which were collected at one data point per second. Once the images are in their respective locations, hyperlinks are set up in ArcMap that allow the respective image to appear at its location when the mouse is hovered over the GPS data point, allowing for visualization of the condition of the bridge decks at defined locations.

## 3.2 Procedures

### 3.2.1 Fall 2015 and Winter 2016 Field Sites

With the assistance of MDOT, the project team selected six large deck bridges located within the MDOT Metro and Grand regions. Each bridge had a bridge deck of at least 95,000 $ft^2$, with deck surface ratings ranging between 5 and 8 (Table 2). These bridges are located in high traffic zones and are near turn-around zones, which aided in the repeating passes across the deck during data collection.

**Table 2: Pilot Study Bridges**

| Str# | MDOT ID | Facility Carried | Facility Intersected | Region | Nickname | Deck Surface Rating | Deck Area (sf) |
|---|---|---|---|---|---|---|---|
| 7966 | 63103-S05 | I-696 | I-75 & 4 ramps | Metro | I-696 / I-75 | 7 | 102,207 |
| 11467 | 82112-S34-8 | M-102 | M-10 & ramps | Metro | 8 MILE | 8 | 167,662 |
| 11627 | 82191-B03-1 | I-75NB | Goddard Rd/Sexton Kilfoil Drain | Metro | Allen Park | 5 | 95,013 |
| 11628 | 82191-B03-2 | I-75 SB | Goddard Rd/Sexton Kilfoil Drain | Metro | Allen Park | 5 | 97,401 |
| 12868 | 41131-S20-1 | US-131 NB | Grandville Avenue | Grand | S CURVE (NB) | 8 | 115,924 |
| 12869 | 41131-S20-2 | US-131 SB | Grandville Avenue | Grand | S CURVE (SB) | 8 | 98,091 |

For the 3DOBS accuracy assessment, the project team attempted to locate a local (near Ann Arbor, Michigan) bridge that contained the presence of a number of visible spalls on the bridge deck. However, after visiting multiple bridges whose bridge inspection reports indicated spalls present on the bridge deck, it was determined that none had the required bridge deck condition necessary for the accuracy assessment. Therefore, with MDOT's assistance, the Lake Nepessing Bridge (Structure Number: 5330) was identified (Table 3). The accuracy assessment was conducted on this bridge due to the high number of spall features located on the bridge deck and a relatively low traffic volume.

**Table 3: Bridge for 3DOBS Accuracy Assessment**

| Str# | MDOT ID | Facility Carried | Facility Intersected | Region | Nickname | Deck Surface Rating | Deck Area (sf) |
|---|---|---|---|---|---|---|---|
| 5330 | 44043-S04 | Lake Nepessing | I-69 | Bay | Lake Nepessing | 3 | 11,721 |

#### *3.2.1.1 M-102 (8 Mile) (StrID: 11467)*

The M-102 (8 Mile) Bridge located in Detroit, Michigan (Metro Region, Wayne County; Structure ID: 11467) has an overall structure condition of "fair (6)". Built in 1965, and reconstructed in 2009, this MDOT owned "big bridge" is 1,838.4 feet in length and consists of three main spans and 12 approach spans. The most recent inspection was conducted in August 2014, and reported that the bridge deck had narrow random cracks scattered across the deck surface, with a rating of "8". Additionally, the inspection report did not indicate the presence of spalls on the bridge deck. At the request of MDOT, MTRI filed a Right-of-Way Construction Permit (#: 82141-033558-15-091415), followed by an Advanced Notice and a Completion Notice.

Field data collection was conducted on September 14, 2015 during late-morning and early-afternoon hours. Setup of 3DOBS, the thermal infrared camera, and BVRCS occurred at the former Northland Shopping Mall center, located about a half-mile from the bridge site. Thermal infrared, 3DOBS, and BVRCS data were collected in unison as the vehicle drove along the right and left sides of each lane to ensure both the optical and thermal imagery would overlap within GIS software. Upon completion of the data collection, all equipment was disassembled at the former shopping center.

#### *3.2.1.2 US-131 NB/SB (StrID: 12868/12869)*

The US-131 Northbound bridge located in Grand Rapids, Michigan (Grand Region, Kent County; Structure ID: 12868) has an overall structure condition of "good (8)". Built in 1999, this MDOT owned "big bridge" is 1,605.64 feet in length and consists of nine main spans and zero approach spans. The most recent inspection was conducted in December 2014, and reported that the bridge deck had narrow random cracks scattered across the deck surface, with a deck surface rating of "8". Additionally, the inspection report did not indicate the presence of spalls on the bridge deck. MTRI filed a Right-of-Way Construction Permit (#: 41131-033450-15-081715), followed by an Advanced Notice and a Completion Notice.

The US-131 Southbound bridge located in Grand Rapids, Michigan (Grand Region, Kent County; Structure ID: 12869) has an overall structure condition of "good (7)". Built in 1999, this MDOT owned "big bridge" is 1,358.60 feet in length and consists of eight main spans and zero approach spans. The most recent inspection was conducted in December 2014, and reported that the bridge deck had narrow random cracks scattered across the deck surface, with a deck surface rating of "8". Additionally, the inspection report did not indicate the presence of spalls on the bridge deck. MTRI filed a Right-of-Way Construction Permit (#: 41131-033556-15-081715), followed by an Advanced Notice and a Completion Notice.

Field data collection was conducted on September 15-16, 2015 during late-morning and early-afternoon hours. Setup of 3DOBS, the thermal infrared camera, and BVRCS occurred at the local hotel, located about four miles from the bridge site. For each lane of the bridge, thermal infrared, 3DOBS, and BVRCS data were collected in unison as the vehicle drove along the right and left sides to ensure both the optical and thermal imagery would overlap within GIS software. During the first attempt to collect data on the northbound lanes on September 15, speed of the data collection vehicle was reduced by traffic incident congestion, leading to the inability to collect data on the northbound bridge. Therefore, the data for the southbound bridge was only collected on this date. Due to the traffic backup on the northbound lanes, the Red Epic sensor (as part of 3DOBS) ran out of memory and the battery charge was low. The remaining data was collected for both north and southbound bridges on September 16$^{th}$.

### *3.2.1.3 I-75 NB/SB (StrID: 11627/11628)*

The I-75 Northbound bridge located in Allen Park, Michigan (Metro Region, Wayne County; Structure ID: 11627) has an overall structure condition of "poor condition (4)". Built in 1966, this MDOT owned "big bridge" is 1,938.32 feet in length and consists of 27 main spans and five approach spans. The most recent inspection was conducted in July 2014, and reported that the bridge deck was between 2% and 10% spalled, delaminated or heavily map cracked, with a deck surface rating of "5". MTRI filed a Right-of-Way Construction Permit (#: 82191- 033559-15-081215), followed by an Advanced Notice and a Completion Notice.

The I-75 Southbound bridge located in Allen Park, Michigan (Metro Region, Wayne County; Structure ID: 11628) has an overall structure condition of "poor condition (4)". Built in 1966, this MDOT owned "big bridge" is 1,992.49 feet in length and consists of six main spans and 27 approach spans. The most recent inspection was conducted in July 2014, and reported that the bridge deck had many areas of scattered spalls and heavy leaching map cracked areas, with a deck surface rating of "5". MTRI filed a Right-of-Way Construction Permit (#:82191- 033560-15-081215), followed by an Advanced Notice and a Completion Notice.

Field data collection was conducted on September 17, 2015 during the mid-to-late morning hours. Setup of 3DOBS, the thermal infrared camera, and BVRCS occurred at the local gas station, located about 1.5 miles from the bridge site. Thermal infrared, 3DOBS, and BVRCS data were collected in unison as the vehicle drove along the right and left sides of each lane to ensure both the optical and thermal imagery would overlap within GIS software. During the data collection at each bridge, MDOT provided two mobile traffic control vehicles to assist the project team (Figure 10). This proved especially useful at the I-75 bridges as traffic was heavier at this location. Upon completion of the data collection, all equipment was transferred to the I-696 bridge location.

**Figure 10: MDOT provided traffic control vehicles at the I-75 NB/SB and I-696 bridge locations.**

### *3.2.1.4 I-696 (StrID: 7966)*

The I-696 Bridge located in Royal Oak, Michigan (Metro Region, Oakland County; Structure ID: 7966) has an overall structure condition of "good (7)". Built in 1971, this MDOT owned "big bridge" is 670 feet in length and consists of three main spans and 2 approach spans. The most recent inspection was conducted in July 2014, and reported that the bridge deck had spalling equating to approximately 25 $ft^2$ scattered across the deck surface, with a deck surface rating of "7". At the request of MDOT, MTRI filed a Right-of-Way Construction Permit (#: 63101-033557-15-

081015), followed by an Advanced Notice and a Completion Notice.

Field data collection was conducted on September 17, 2015 during early-afternoon hours. Setup of 3DOBS, the thermal infrared camera, and BVRCS occurred in the parking lot of a local hotel, located about a 1.5 miles the bridge site. Thermal infrared, 3DOBS, and BVRCS data were collected in unison as the collection vehicle drove along the right and left sides of each lane to ensure both the optical and thermal imagery would overlap within GIS software. MDOT again assisted the project team by providing the two mobile traffic control vehicles. These vehicles proved very useful as traffic was congested leading up to the bridge. Upon completion of the data collection, all equipment was disassembled in the local hotel's parking lot.

### 3.3.2 3DOBS Accuracy Assessment

For the 3DOBS accuracy assessment task, MTRI had difficulty locating a local bridge with the presence of multiple spalls on the bridge deck. Therefore, it was requested that MDOT assist in the bridge selection. The Lake Nepessing Bridge located near Lapeer, Michigan (Bay Region, Lapeer County; Structure ID: 5330) has an overall structure condition of "poor (4)". Built in 1971, this MDOT owned bridge is 264 feet in length and consists of two main spans and zero approach spans. The most recent inspection was conducted in January 2016, and reported that the bridge deck had numerous asphalt patched spalls, several open spalls in both lanes, and a total area of spalling, patching, and delamination estimated at 25%, with a rating of "4". At the request of MDOT, MTRI filed a Right-of-Way Construction Permit (#: 44043-036785-16- 012116), followed by an Advanced Notice and a Completion Notice.

Field data collection was conducted on February 23, 2016 and lasted about six hours (9 am – 3 pm). MDOT provided traffic control for the two-lane structure, which closed a single lane at a time, allowing the field data collection while traffic could pass (Figure 11). Setup of 3DOBS and BVRCS took place onsite at the bridge. For each lane of the bridge, MTRI constructed a 10 ft by 8 ft grid that extended across the entire deck. This is intended to assists in the 3-D reconstruction of the bridge deck during data processing and to offer another method of check 3D reconstruction accuracy. After the grid was created, spalling and patching areas along the bridge deck were marked and manually measured (length, width, and depth) to provide ground truth data for comparison to the reconstructed model (Figure 12). After these measurements were made 3DOBS and BVRCS data were collected in unison as the data collection vehicle drove along the right and left side of each lane (Figure 13). After a single lane's worth of data was collected, MDOT traffic control closed the other lane, where the same procedures were conducted to collect the 3DOBS and BVRCS data.

**Figure 11: The Lake Nepessing Rd bridge deck was closed to traffic one lane at a time.**

**Figure 12: Manual measurements the length, width, and depth of spall and patch features on the bridge deck.**

**Figure 13: 3DOBS and BVRCS data collection was conducted in unison as the vehicle drove each lane of the bridge.**

# 4. Findings

## 4.1 Summary of Remote Sensing Technologies

The following sections overview data collected by each of the remote sensing technologies, including the amount of data, file size, and any complications encountered during the data collection events.

### 4.1.1 3DOBS

The collection of 3DOBS data went mostly as planned. The only issue encountered was the wireless connection between the RED Epic and the remote control occasionally dropped. For the most part this was quickly resolved in the vehicle. However, on two occasions the team had to recollect a pass since the remote control didn't connect in time to start recording prior to the first bridge joint. If this occurred while collecting data, the camera would continue to take video of the deck but would not respond to commands until the connection was regained. On two occasions, one at 8 Mile and one at US-131, the team had to pull into a parking lot to restart and reconnect the remote control and the RED Epic camera, adding an additional 10 minutes to the overall collection time. This issue did not occur during the Lake Nepessing Rd accuracy assessment data collection.

During the data collections, two 64 GB and two 240 GB SSDs were used to store the RED Epic video files. Table 4 displays the total size of all the videos taken of the bridge decks for each pilot study bridge. These file sizes do not directly correlate to how large the bridge deck is and, therefore, cannot be scaled for future collection estimates. They are displayed to show an example of the amount of SSD storage capacity that may be needed for future collections on large deck bridges.

**Table 4: Total size of all video files collected at each pilot study bridge deck.**

| Bridge | No. Passes | Total File Size (GB) |
|---|---|---|
| M-102 (8 Mile) | 12 | 78.5 |
| US-131 NB/SB | 18 | 43.6 |
| I-75 NB/SB | 12 | 124.0 |
| I-696 | 16 | 187.0 |

The total video file size for each of these bridges depends of a variety of factors. One factor is that the project team starts recording video prior to reaching the first bridge joint of the bridge being inspected. This starting point is not a set distance and therefore varies in length of time on the video. The main factor that impacted these file sizes is the connection between the RED Epic and the remote control. At times the connection would drop during a pass and would be restored at some point after the team had already driven passed the bridge.

While collecting on I-75 and I-696 the team used the 240 GB SSDs and instead of stopping the collect to restart the RED Epic and remote control, the team allowed the camera to continuously collect data between multiple passes until connectivity was regained. This led to the significantly larger file sizes. In general, the RED Epic has a data rate of about 79 MB/sec and will fill a 64 GB SSD after 14 minutes of recording, or a 240 GB SSD after 52 minutes of recording at full resolution.

Once the data was brought back to the lab, frame extraction and geotagging of the RED Epic frames began. The most time consuming part of preparing the RED Epic data for processing is extracting the frames for the video files. First, the analyst needs to determine the beginning and ending points of the pass to be extracted. For videos taken on I-75 and I-696 in which the RED Epic recorded video over several passes, this could take up to 30 minutes for locating a single pass. For most other video files, which only contain a single pass, this process took no more than five minutes. The next step of deleting duplicate frames continued much faster because the process was entirely automated.

Geotagging photos were partially automated with some required manual preparatory work. The manual work included converting the GPS data into a useful format. First, each run was extracted from the GPS data to determine the starting frame and GPS point. Because the Trimble is continuously collecting a track log during the entire collection, there are many points captured that are not needed for processing bridge deck condition data. Next, individual passes are extracted from the track log in ArcMap. Additional points are interpolated through an automated process as shown in Figure 14. After the additional points are interpolated in each pass, a starting frame and GPS point needed to be identified to start the geotagging process as each successive frame corresponds to the following GPS point.

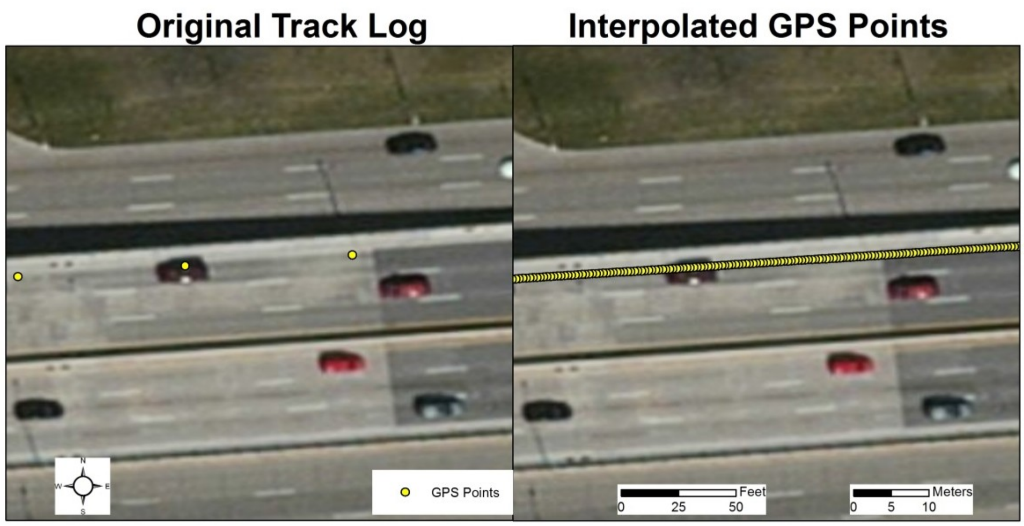


**Figure 14: 8 Mile Rd with original and extracted GPS points for the westbound right lane pass.**

After the RED Epic frames were geotagged, each frame was imported into Agisoft for processing. This however was challenging at first due to the bridge decks being relatively flat with little or no spalling. During the original project and reported in MDOT RC-1617 it was determined that height variation of the modeled surface is essential for Agisoft to perform 3D modeling (Ahlborn and Brooks, 2015). Adding additional overlap of the imagery, such as collecting multiple passes per lane, aids in scene reconstruction when the surface is relatively flat. This was done for Freer Rd in 2014 where the project team did three passes per lane (right, center, and left). For this pilot project, two passes were collected per lane in an effort to overcome the mostly flat surfaces of the selected bridge decks.

Despite having the extra overlap, the project team was unable to reconstruct 3D models of the bridge decks early in the project. As noted by the high deck surface rating of 8, the 8 Mile Rd bridge deck did not contain any spalling, I-696 and US-131 NB/SB had very few and small spalls, and I-75 NB/SB had more spalls and patching than the others, but was still a mostly flat surface with few distresses. The resulting models would be severely distorted and not of sufficient quality to make reliable and accurate measurements (Figure 15). Because the RED Epic imagery was unable to be processed into an orthoimage and DEM, the imagery was mosaicked and georeferenced to the high-resolution base maps layer within ArcGIS. While this process is more time consuming, it provided a high-resolution base layer for manually georeferencing the thermal imagery and spalls.

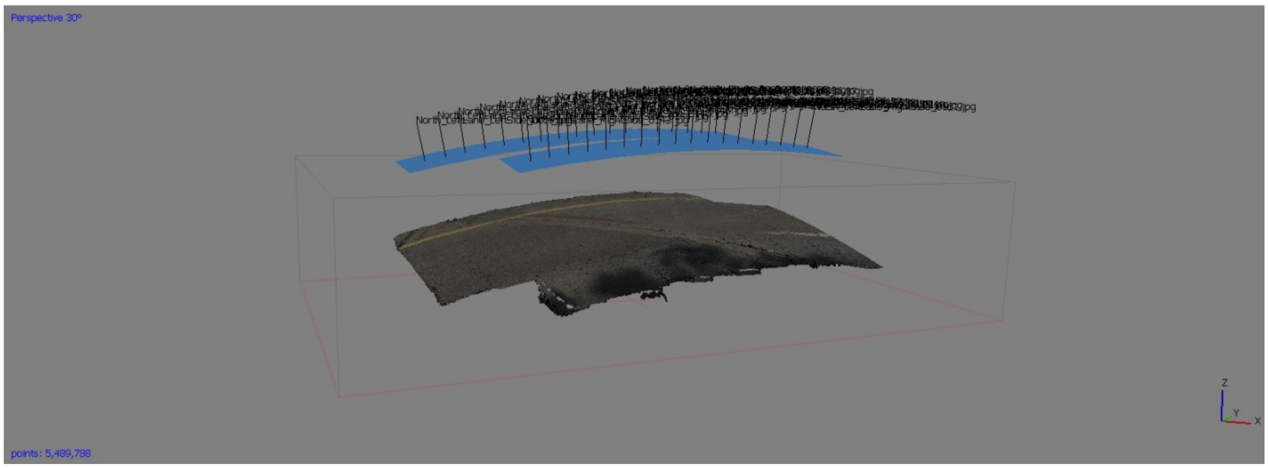


**Figure 15: Example of I-75 point cloud demonstrating the reconstruction challenges encountered.**

While the RED Epic imagery was being mosaicked for each of the large deck bridges, further investigation into the Agisoft reconstruction errors continued. The problems persisted even when a set of frames containing spalls and patches on I-75 would either fail in reconstruction or would model correctly in Agisoft but the resulting DEM and orthoimage would be incorrectly positioned or orientated. During this time a lens correction was attempted using Agisoft Lens to attempt to remove the distortion in the frames in an effort to aid in 3D reconstruction. While the lens correction did reduce some of the errors, it did not solve the incorrect placement of the DEM and orthoimage or the model distortion and orientation issues.

This led to an additional set of tests to be performed on the Lake Nepessing Rd Bridge during the 3DOBS accuracy assessment task. The first test was designed to assess whether camera resolution was limiting the ability to reconstruct models and included data collection using the Nikon D800. With a 36.3 MP sensor, the resolution of the Nikon D800 imagery is more than twice that of the RED Epic. The other test was to add ground control markers in a grid pattern on the deck to determine the impact of placing grid patterns. This latter method was used in the original *USDOT/RITA Bridge Condition Assessment Using Remote Sensors* project prior to Agisoft PhotoScan having the capability to use the coordinates of geotagged imagery (Ahlborn et al, 2013).

While working with the Lake Nepessing data, it was discovered that newer versions of Agisoft PhotoScan beyond version 1.0, which the project team had been using, required the addition of camera orientation parameters when using only geotagged imagery without ground control markers. These orientation parameters include the roll, pitch, and yaw of the camera. For 3DOBS data collections where the camera was mounted to a vehicle looking down at the deck, roll refers to the camera rotated left or right from nadir, pitch is the camera rotated towards or away from the vehicle, and yaw is the cardinal direction the top of the camera is facing. These parameters had been estimated in previous versions of Agisoft with the user having the ability to manually adjust the orientation of the model. It is now required to add a text file that includes the roll, pitch, and yaw of each camera position to set the orientation for Agisoft PhotoScan versions beyond 1.0.

With the additional orientation defined, the north and southbound lanes of Lake Nepessing Rd were successfully reconstructed using only the geotagged RED frames. A 20 ft section of southbound I-75 using only the geotagged frames was processed as an example. Figure 16 shows the orthoimage, DEM, and Hillshade of this section. There are still parts of the 3D model, such as the edges and the center, where there is increased noise resulting in a jagged appearance in the DEM and Hillshade. This is a result of a flat road surface in the center of the model and reduced overlap at the edges. By comparison, the areas that contain the bridge joint and patching has less noise because there was more height variation.

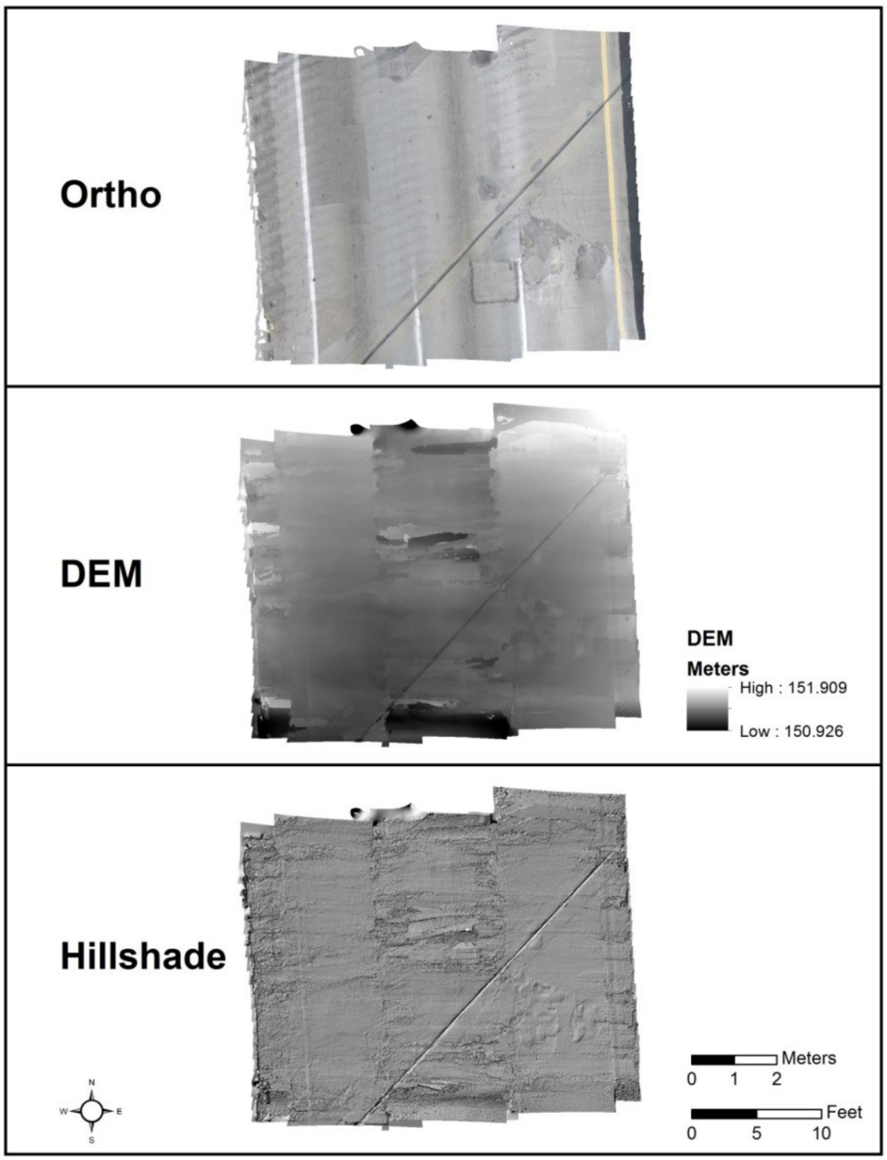


**Figure 16: A roughly 20 ft section of I-75 SB processed through Agisoft using geotagged imagery and orientation parameters.**

Including additional orientation information did not improve reconstruction modeling for all of the bridges in this study. However, I-696 and US-131 NB/SB, with deck surface ratings of 7 and 8/8, respectively, are very flat with very little spalling and patching, as compared to I-75 NB/SB. While adding camera orientation information was able to aid in the reconstruction of bridge decks with some height varying features, it was unable to correctly model those decks with no height variation. Figure 17 shows and example of a small section of the left lane of eastbound I-696, which was reconstructed using the additional orientation information. There is a 6 ft difference in lane width between the east and west side of the model and incorrect spatial position, showing that even with the additional information, excellent condition deck surfaces may not be accurately reconstructed.

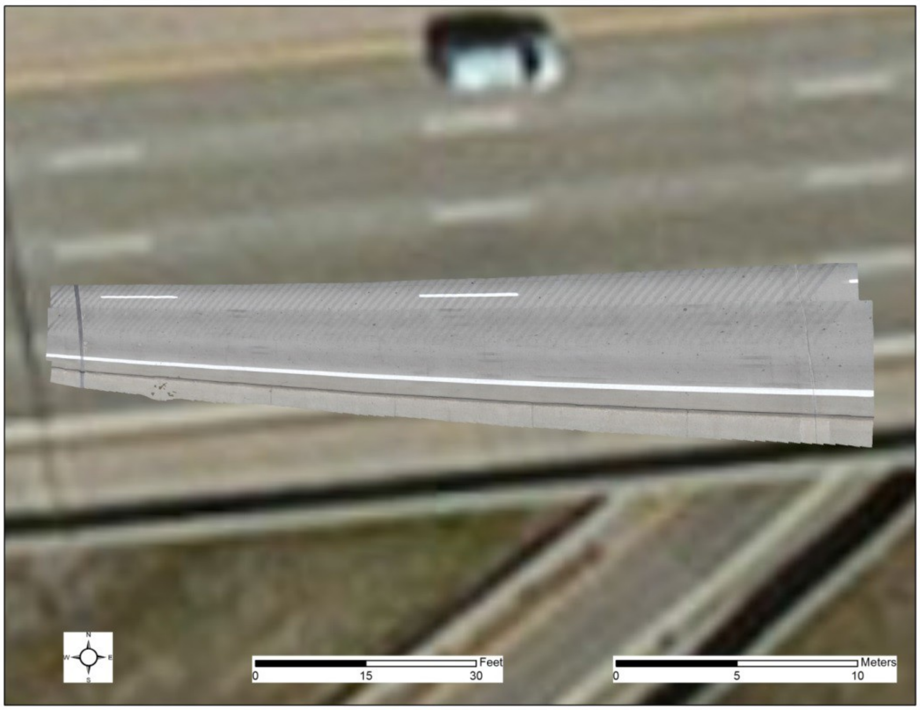


**Figure 17: A section of I-696 modeled in Agisoft using geotagged RED imagery and camera orientation information.**

### 4.1.2 Passive Infrared Thermography

After the raw imagery was processed and potential delaminations were identified for each image, the processed images were merged into a single composite image for each bridge deck. The composite images were created using the same script written at MTRI that merged the optical images together. The merged thermal image was then georeferenced to each bridge deck. All potential delaminations within the process imagery were then digitized, allowing each to be identified and quantified. Table 5 indicates the number of potential delaminations for each bridge deck identified using infrared thermography, the approximate area, and the percentage of bridge deck that is impacted.

**Table 5: Potential delaminations for each bridge deck as determined via thermal imagery.**

| Bridge Deck | Number of Potential Delaminations | Area of Potential Delaminations ($ft^2$) | % of Bridge Deck Area |
|---|---|---|---|
| M-102 (8 Mile) | 398 | 2,942.12 | 1.70% |
| US-131 NB | 34 | 150.88 | 0.11% |
| US-131 SB | 90 | 344.97 | 0.33% |
| I-75 NB | 529 | 2,203.75 | 2.33% |
| I-75 SB | 1,410 | 14,119.17 | 14.14% |
| I-696 | 203 | 1,125.30 | 1.12% |

The two US-131 bridge decks were difficult for the project team to analyze. According to MDOT's Structure Inventory and Appraisal report for US-131 NB and US-131 SB, there is an Epoxy Coated Reinforcing deck protection seal, which was emitting a lot of heat energy and showing a lot of inconsistencies on the surface. This caused issues with locating potential delaminations as the deck protection seal reflected infrared, which made the bridge deck and delaminations appear similar in temperature, significantly reduced the contrast in the thermal imagery. This did not prevent the analysis, but made the analysis more difficult and took longer than expected.

### 4.1.3 Bridge Viewer Remote Camera System

Upon importing the GeoJot+ created shapefile containing the GPS data and corresponding GoPro Hero3 imagery into ArcMap, making manually edits, and setting up hyperlinks that allowed end users to view the image corresponding to each GPS point, the overall bridge deck condition can be viewed via BVRCS imagery. Approximately 1,100, 500, 300, 450, 400,and 680 images were captured and geotagged by the BVRCS for the 8 Mile, US-131 NB, US-131 SB, I-75 NB, I-75SB, I-696 bridges, respectively (Figures 18, 19, 20, and 21).

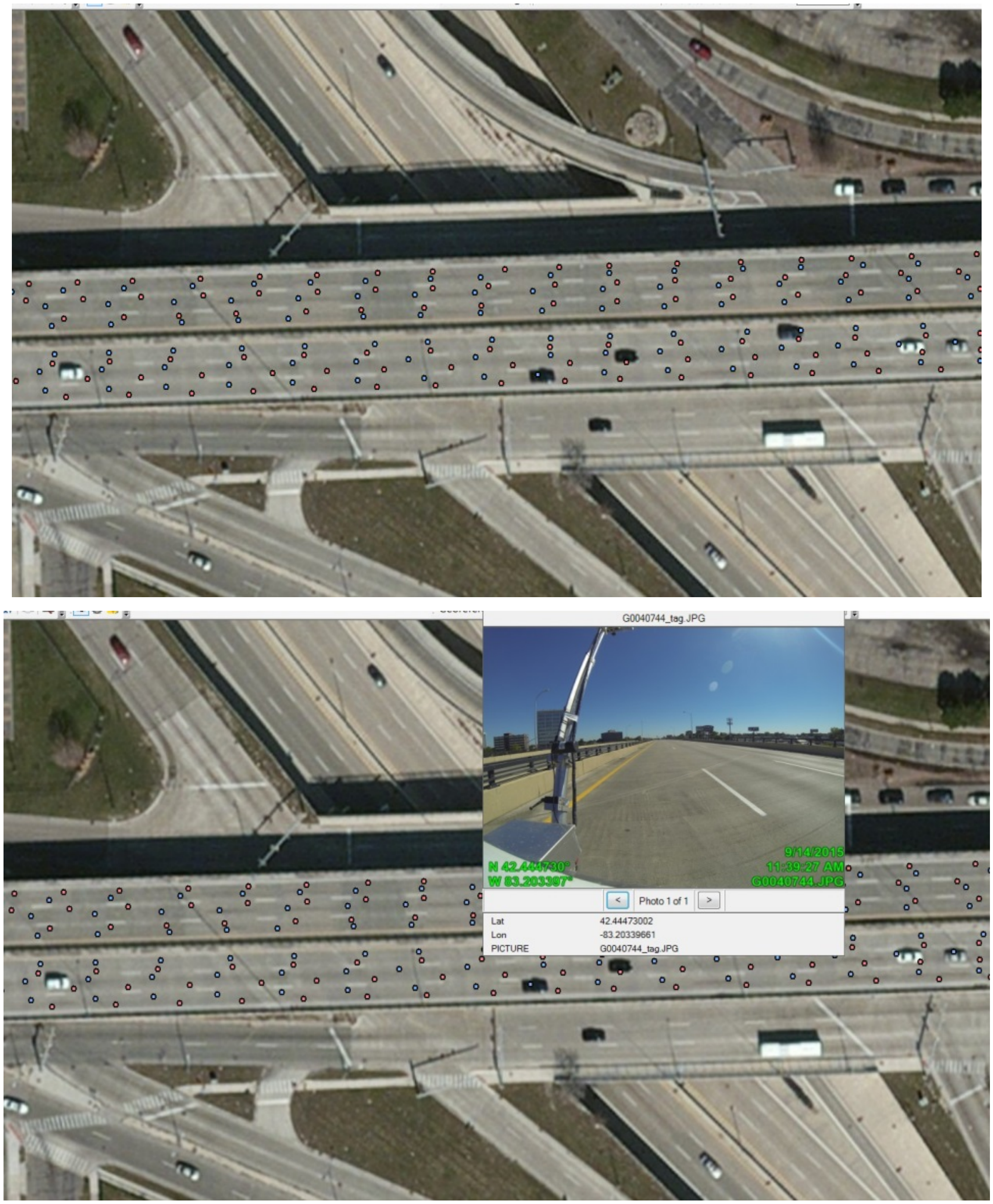


**Figure 18: A subset of the 8 Mile Bridge with BVRCS GPS data placed on the bridge (top) and the image showing the bridge deck section that corresponds to the GPS data point (bottom).**

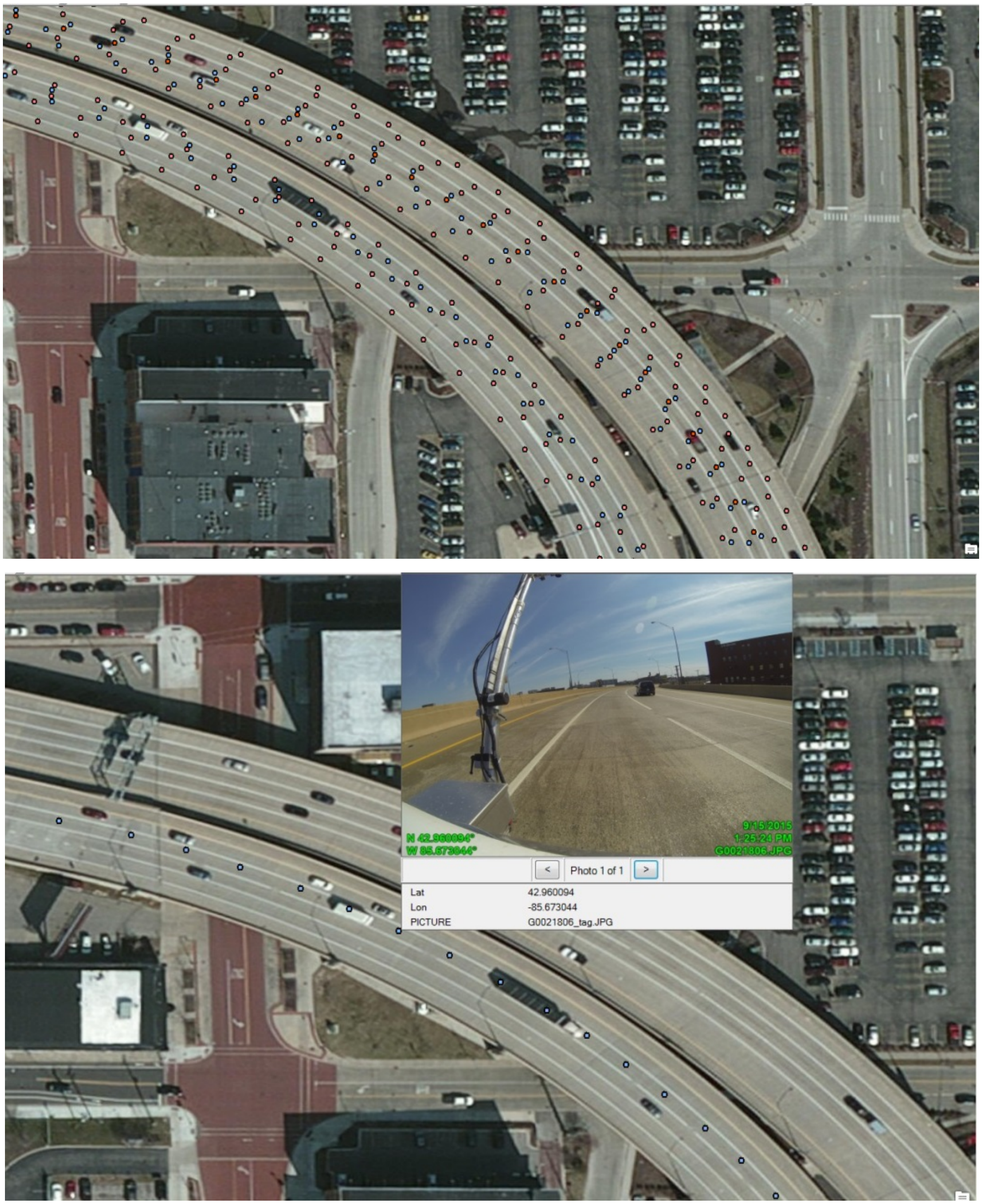


**Figure 19: A subset of the US-131 NB/SB Bridges with BVRCS GPS data placed on the bridge (top) and the image showing the bridge deck section that corresponds to the GPS data point (bottom).**


**Figure 20: A subset of the I-75 NB/SB Bridges with BVRCS GPS data placed on the bridge (top) and the image showing the bridge deck section that corresponds to the GPS data point (bottom).**

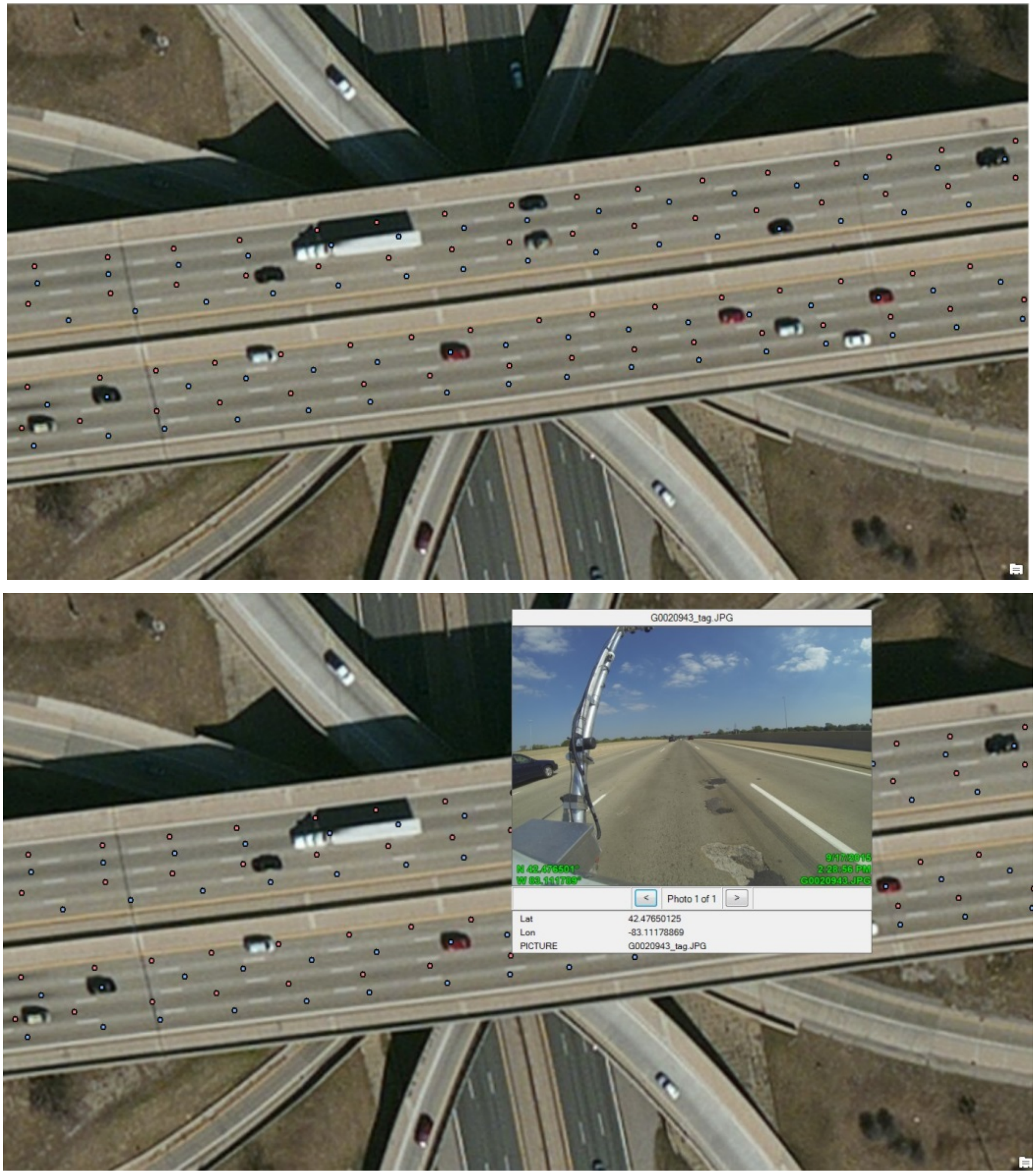


**Figure 21: A subset of the I-696 Bridge with BVRCS GPS data placed on the bridge (top) and the image showing the bridge deck section that corresponds to the GPS data point (bottom).**

### *4.3 Analytical Methods and Results*

Before data collection began at each bridge location, both the RED Epic optical and FLIR thermal cameras were attached side-by-side to front of the data collection vehicle (Figure 22). Additionally, the BVRCS GoPro Hero 3 cameras were attached to the front of the vehicle. Data collection consisted of driving the vehicle across each bridge multiple times to ensure imagery corresponding to each lane was collected, requiring the vehicle pass over the right and left sides of each lane. During the collections, highway traffic was not restricted and public access to each bridge was allowed. The data collection vehicle remained at highway speeds (approximately 70 mph) leading up to the bridge sites, but slowed down to near-highway speeds (approximately 45mph) when data collection was occurring, and sped back up to the original speed after data collection for each pass was complete.  MDOT assisted by providing shadow vehicles for the I- 75 NB, I-75 SB and I-696 bridges due to higher traffic volumes at those locations.


**Figure 22: The data collection vehicle (left) and both the RED Epic and FLIR thermal infrared cameras attached to the vehicle.**

#### 4.3.1 8 Mile

After processing, merging, and georeferencing both optical and thermal imagery data sets, the outputs were placed within GIS software to provide visualization of distress features. Through using an automated script created to correct the overlap in individual frames extracted from RED Epic video imagery, individual frames were cropped and placed end-to-end, resulting in a single image for subsets of the bridge deck. The subsets were then merged together and georeferenced to ESRI base maps to create a single image per pass over the bridge. For the optical imagery, this serves as the visual basis of the bridge deck. As seen in Figure 23, the separate passes over the bridge deck do not necessarily line up with one another, resulting in slight distortion of pavement markings and bridge joints. However, the merged optical imagery proved useful as it provided an overview of how the bridge deck appeared during data collection. This bridge deck contained no spalls outside of the bridge joint area.

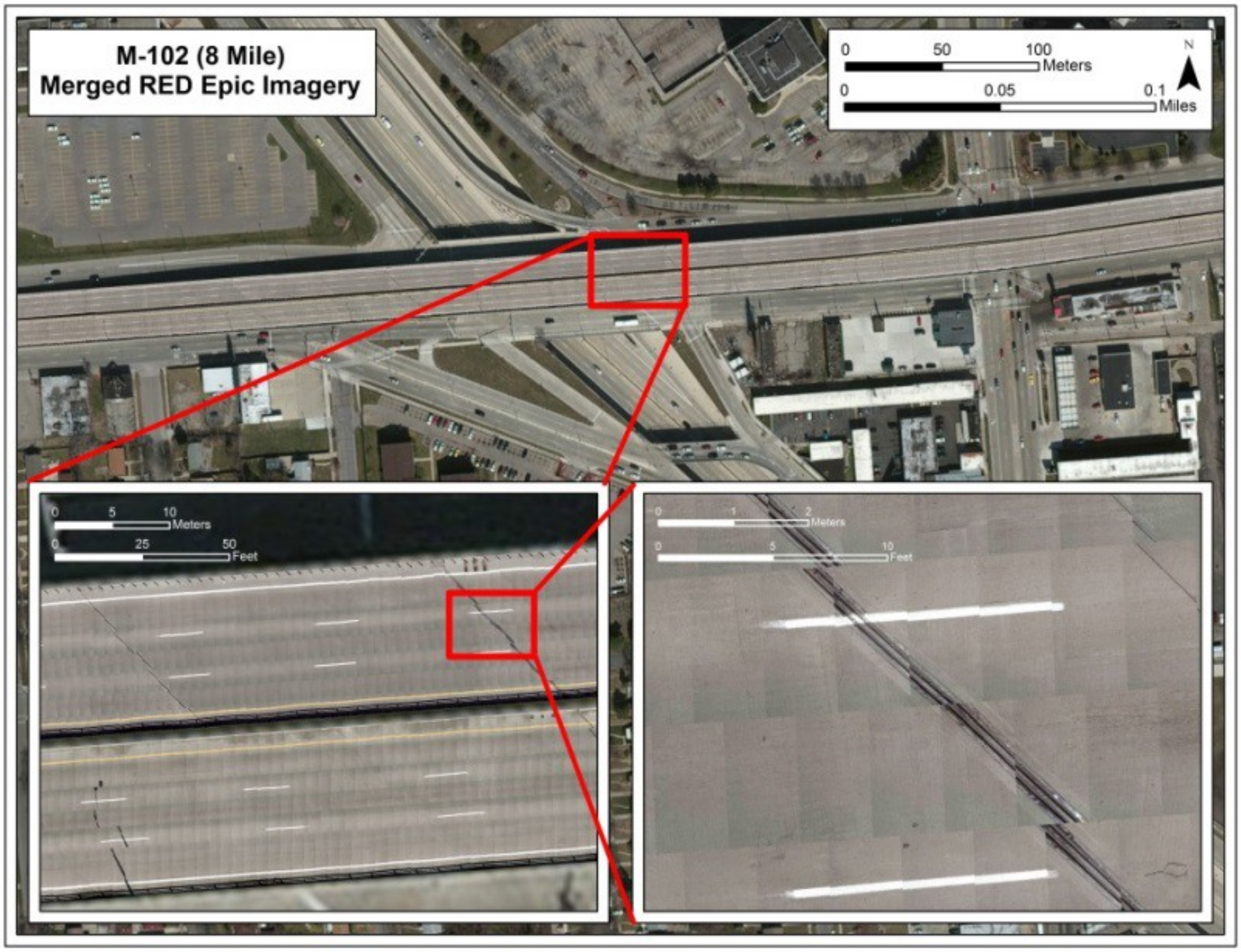


**Figure 23: RED Epic imagery merged together to form spall locations on the bridge deck of M-102 (8 Mile) eastbound and westbound.**

Similarly, the thermal imagery was also merged together through the same automated script. Individual frames were cropped and placed end-to-end, resulting in a single image for subsets of the bridge deck. The subsets were then merged together and georeferenced to ESRI base maps to create a single image per pass over the bridge (Figure 24). GS Infrastructure, Inc. inspected the thermal imagery and indicated any location that appeared to have a potential delamination. The merged optical and thermal images can then be placed on top of another and by using transparent layers in the GIS software; a better overview of where potential delaminations exist on the bridge deck can be seen (Figure 25). In total, 398 potential delaminations were identified by GS Infrastructure, Inc., totaling an area of 2,942 $ft^2$, or approximately 1.73% of the entire bridge deck.

In the visualization of distress features, each feature is color coded by condition state as defined by Element #12 – Reinforced Concrete Deck in the AASHTO Bridge Element Inspection Manual (AASHTO, 2015) and Condition State Table 1 – Reinforced Concrete in the MDOT Bridge Inspection Manual (MDOT, 2015). Condition state levels for defined for Good (CS 1), Fair (CS 2), Poor (CS 3), and Severe (CS 4). For spalling or delaminations of reinforced concrete bridge decks, a condition state of 1 indicates no distress; CS2 is assigned when a spall is 1 in. or less deep, or less than 6 in. diameter, and patching is sound; CS3 is assigned for spalls greater than 1 in. deep or 6 in. diameter. CS4 warrants further structural review to determine the effect on strength or serviceability of the element or the review has been conducted and the distress has been found to impact the strength or serviceability of the bridge deck element. All delaminations are automatically placed into CS2, independent of size. For the overall summary of each span's condition, please reference Figure 40 and Table 8 in Section 4.3.6.

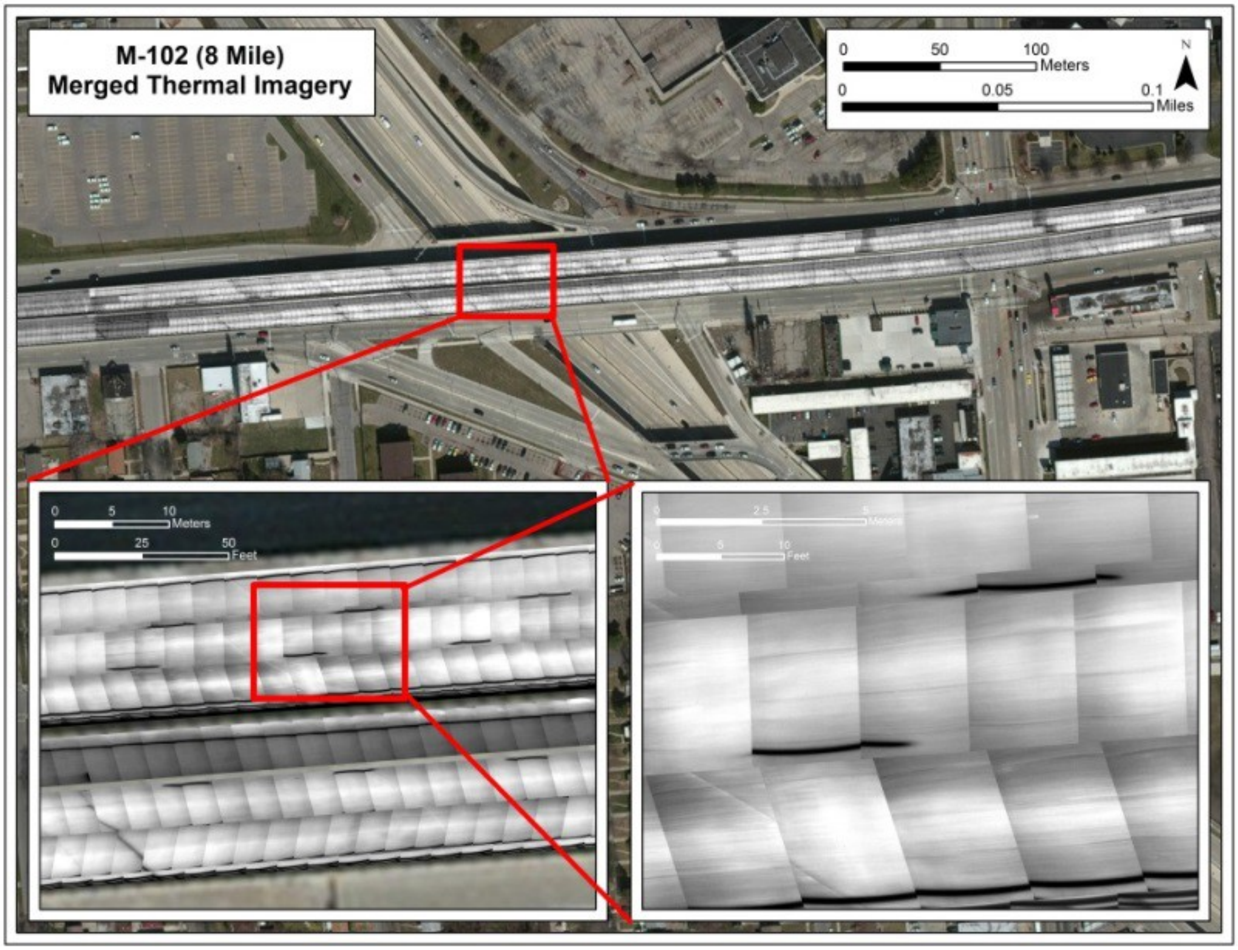


**Figure 24: Merged thermal imagery merged of M-102 (8 Mile) eastbound and westbound bridge decks.**

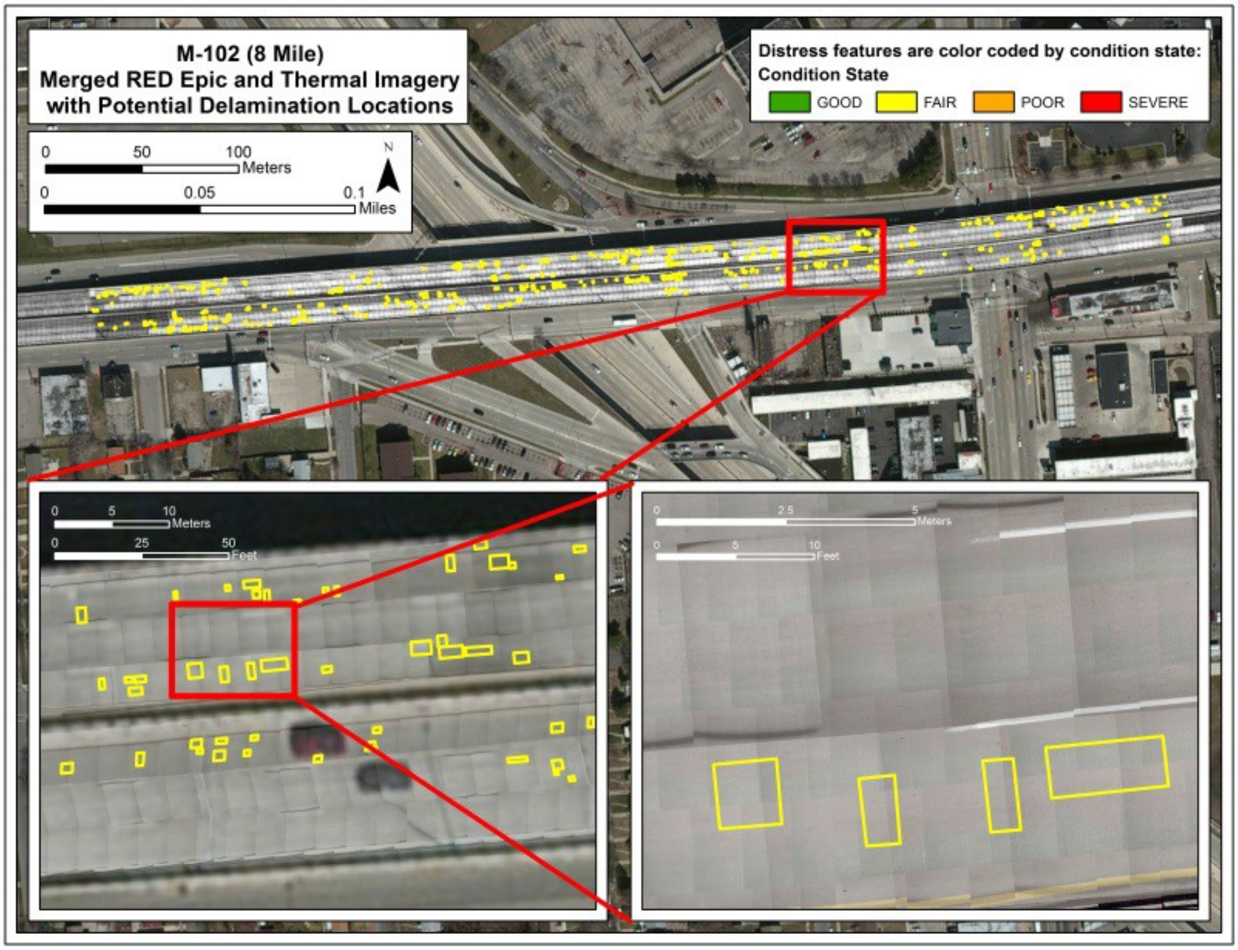


**Figure 25: Locations of potential delaminations for M-102 (8 Mile) eastbound and westbound bridge decks.**

### 4.3.2 US-131 NB/SB

By using the same script that automated the merging of each individual frames extracted from the RED Epic video imagery for the M-102 (8 Mile) bridge deck, a single merged image of US-131 north and southbound bridge decks were created (Figure 26). Similar to the M-102 (8 Mile) bridge deck, the optical image was created though the merging of imagery from the different vehicle passes over each lane. The separate passes over the bridge deck did not line up perfectly with one another, resulting in slight distortion of pavement markings and bridge joints. However, the merged optical imagery proved useful as it provided an overview of how the bridge deck appeared during data collection.

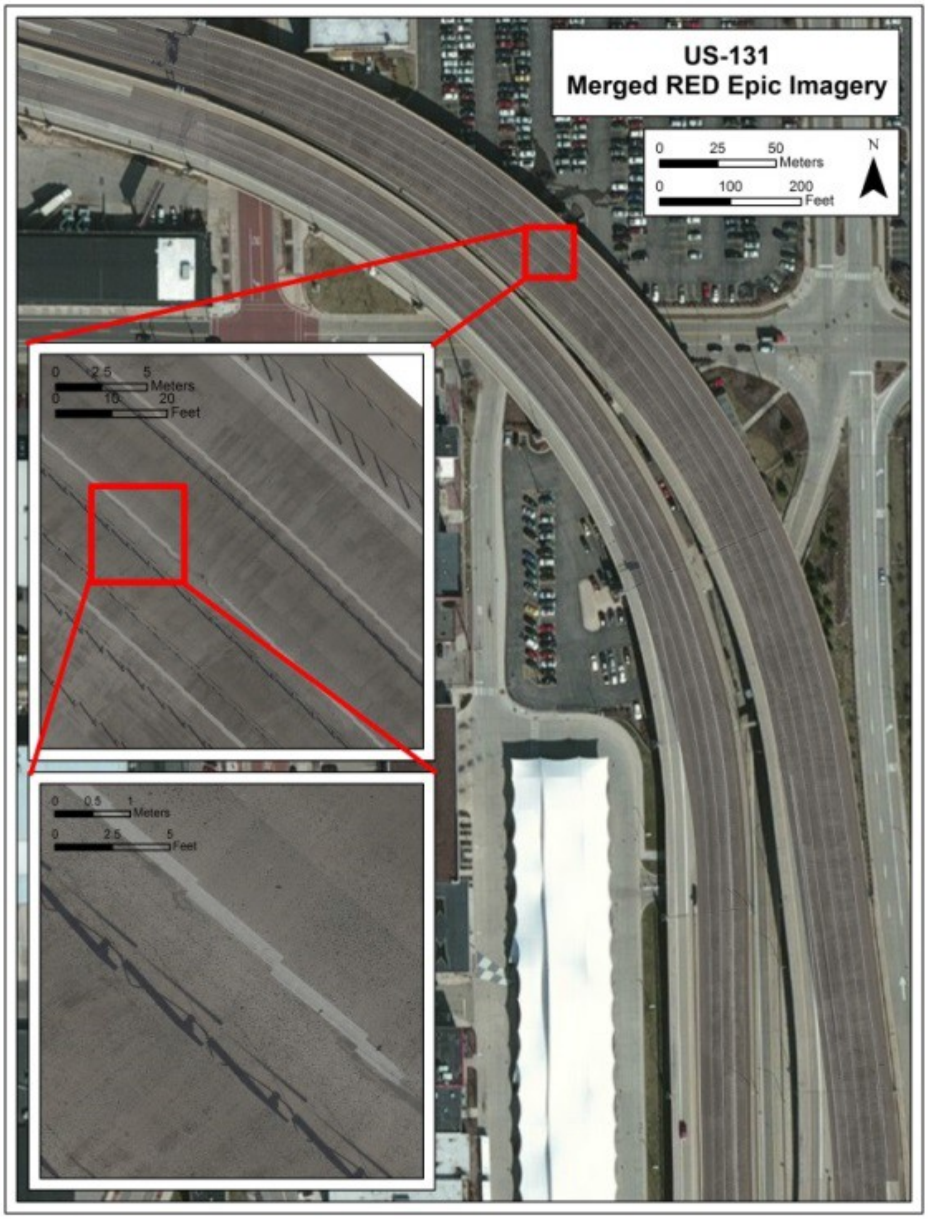


**Figure 26: RED Epic imagery merged together to form the US-131 northbound and southbound bridge decks.**

After merging the thermal imagery from US-131 through the use of the automated merging script, the merged output was georeferenced to ESRI base maps (Figure 27). GS Infrastructure, Inc. inspected the thermal imagery and indicated any location that appeared to have a potential delamination. The merged optical and thermal images were then placed on top of one another and through the use of transparent layers in the GIS software, an overview of potential delaminations and spalls appear on the bridge deck (Figure 28). In total, 133 potential delaminations (34 northbound and 90 southbound) were identified by GS Infrastructure, Inc. totaling an area of 532 $ft^2$, or approximately 0.25% of both bridge decks combined. For the overall summary of each span's condition, please reference figures 41 and 42 and tables 9 and 10 in Section 4.3.6.

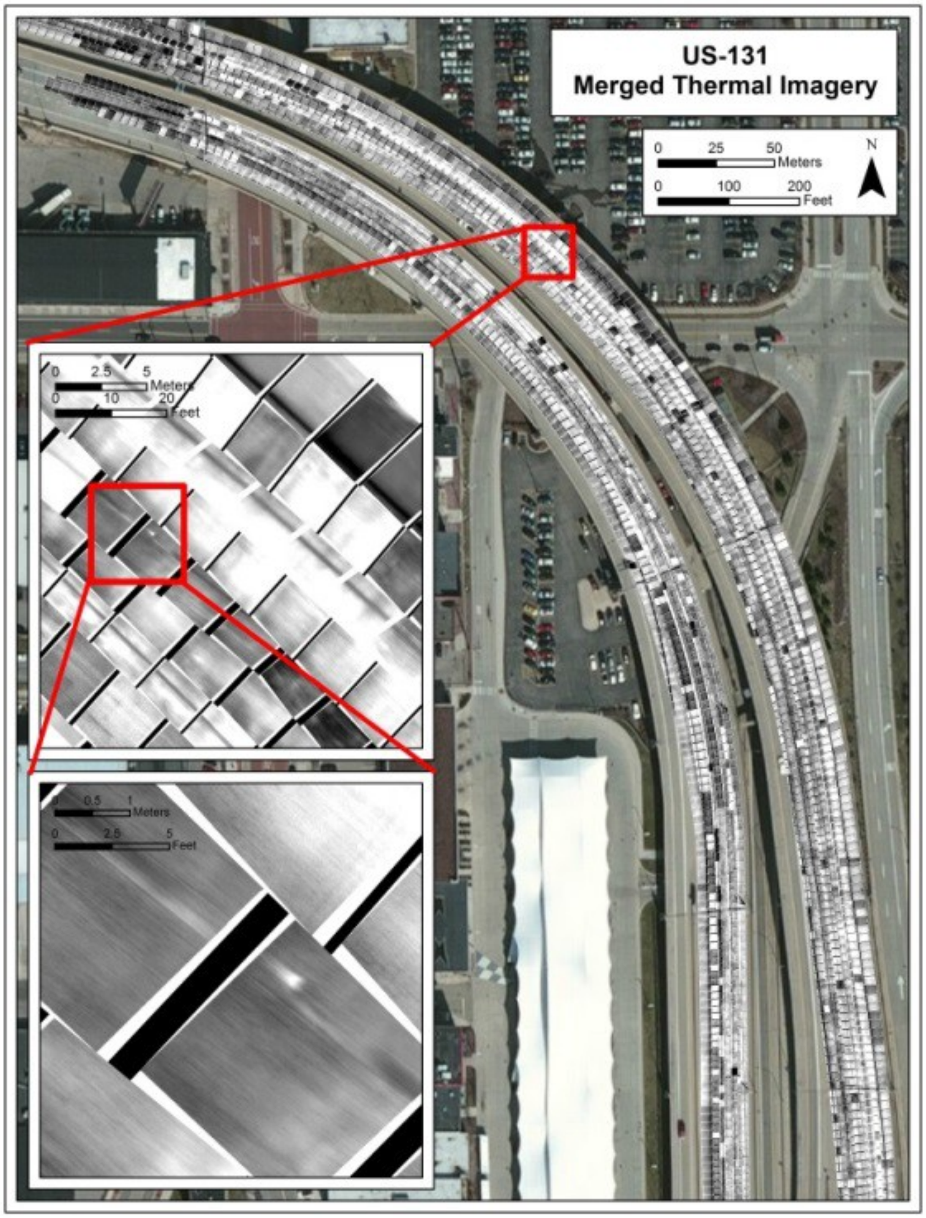


**Figure 27: Merged thermal imagery of US-131 northbound and southbound bridge decks.**

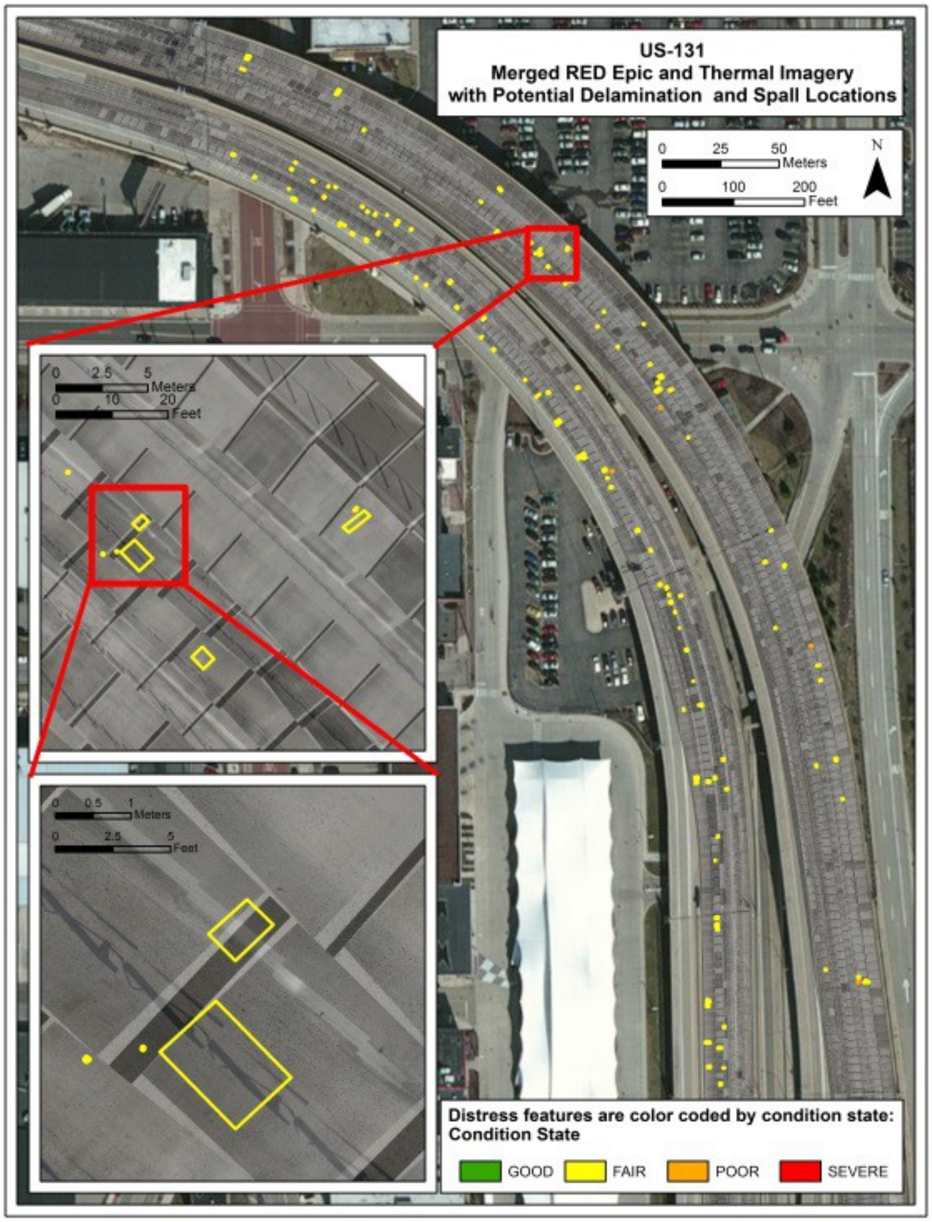


**Figure 28: Location of potential delaminations and spalls on US-131 northbound and southbound bridge decks.**

### 4.3.3 I-75 NB/SB

Upon merging the individual frames from the RED Epic for each separate pass over the bridge decks, a single merged image of the I-75 north and southbound bridge decks was created (Figure 29). Imagery from separate passes over the bridge deck did not line up perfectly with one another, resulting in slight distortion of pavement markings and bridge joints. However, the merged optical imagery proved useful as it provided an overview of how the bridge deck appeared during data collection.

After merging the thermal imagery from I-75 north and southbound decks, respectively, through the use of the automated merging script, the merged output was georeferenced to ESRI base maps (Figure 30). GS Infrastructure, Inc. inspected the thermal imagery and indicated any location that appeared to have a potential delamination. The merged optical and thermal images were then placed on top of one another and through the use of transparent layers in the GIS software, an overview of potential delamination locations and spalling appear on the bridge (Figure 31). In total, 1,877 potential delaminations (515 northbound and 1,362 southbound) were identified by GS Infrastructure, Inc. totaling an area of 16,328 $ft^2$, or approximately 8.50% of both bridge decks combined. As previously noted, spalls and delaminations are color-coded by condition state as noted in AASHTO BEIM (2015). For the overall summary of each span's condition, please reference figures 43 and 44 and tables 11 and 12 in Section 4.3.6.

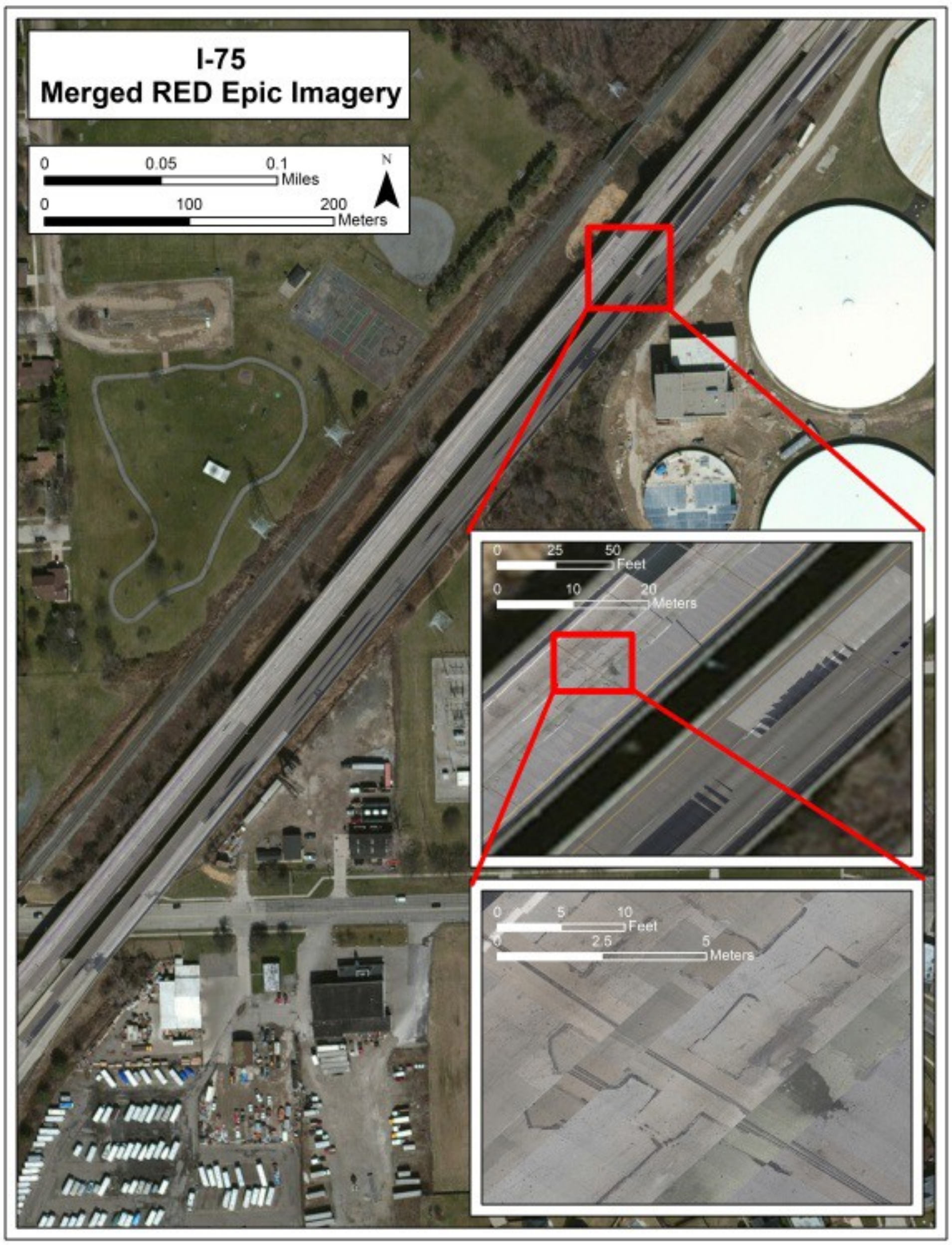


**Figure 29: RED Epic imagery merged together to form I-75 northbound and southbound bridge decks.**

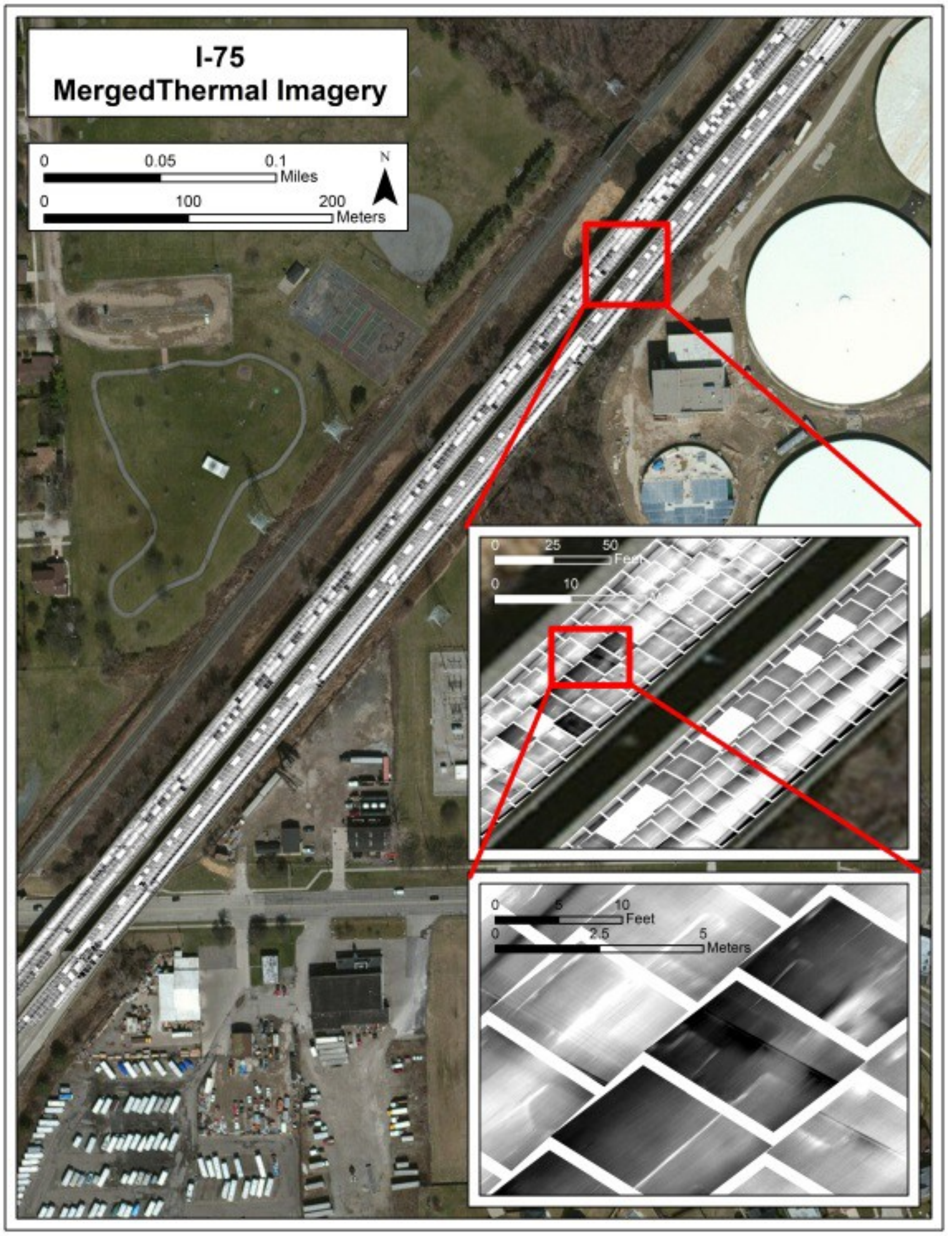


**Figure 30: Merged thermal imagery of I-75 northbound and southbound bridge decks.**

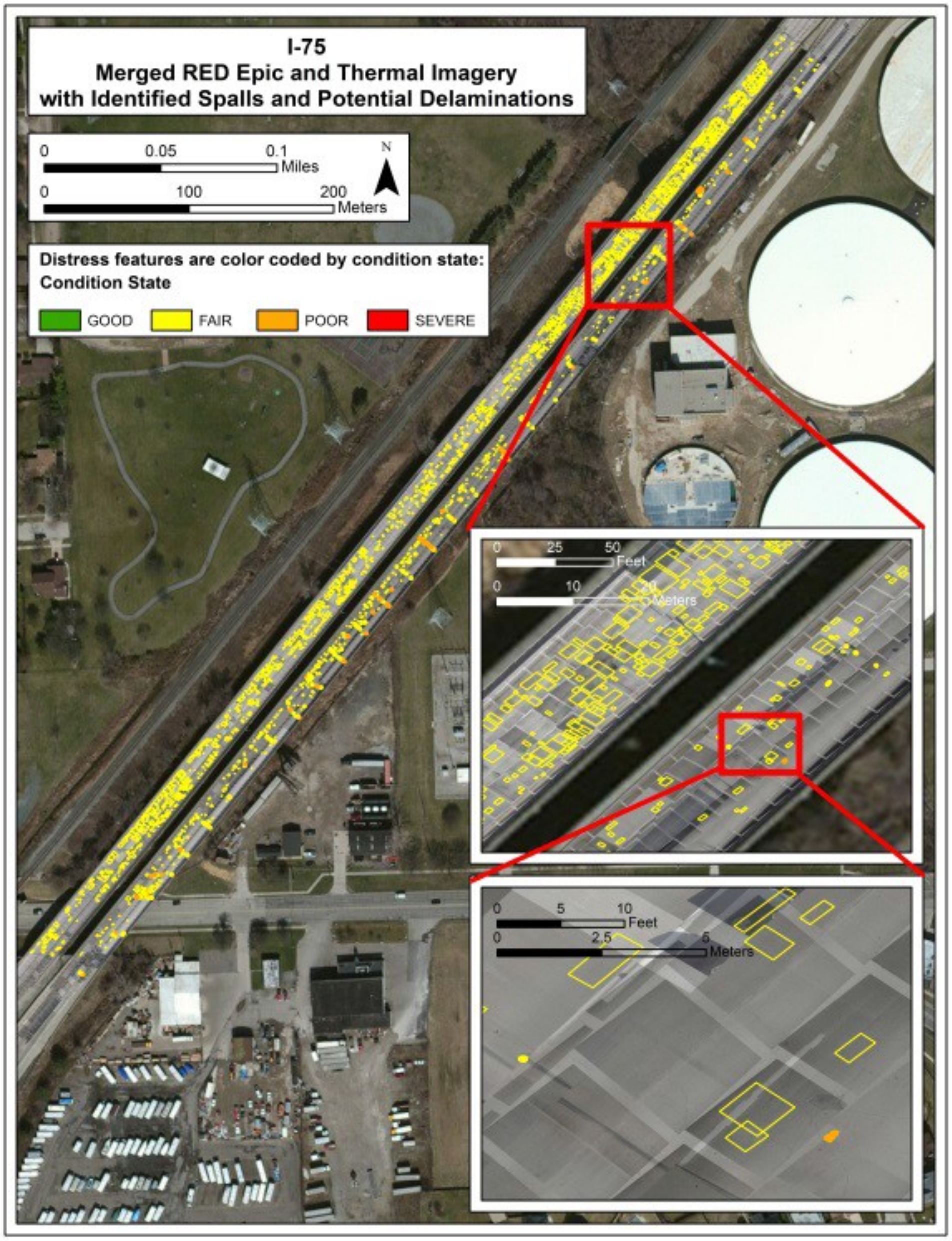


**Figure 31: Location of potential delaminations and spalls for I-75 northbound and southbound decks.**

### 4.3.4 I-696

Upon merging the individual frames from the RED Epic for each separate pass over the bridge decks, a single merged image of the I-696 west and eastbound bridge decks were created (Figure 32). The imagery from the separate passes over the bridge deck did not line up perfectly with one another, resulting in slight distortion of pavement markings and bridge joints. However, the merged optical imagery proved useful as it provided an overview of how the bridge deck appeared during data collection.

After merging the thermal imagery from I-696 through the use of the automated merging script, the merged output was georeferenced to ESRI base maps (Figure 33). GS Infrastructure inspected the thermal imagery and indicated any location that appeared to have a potential delamination. The merged optical and thermal images were then placed on top of one another and through the use of transparent layers in the GIS software, a better overview of where potential delaminations exist and how it appears on the bridge deck can be seen (Figure 34). In total, 203 potential delaminations were identified by GS Infrastructure, Inc., totaling an area of 1,125 ft$^2$, or approximately 1.10%. For the overall summary of each span's condition, please reference Figure 45 and Table 13 in Section 4.3.6.

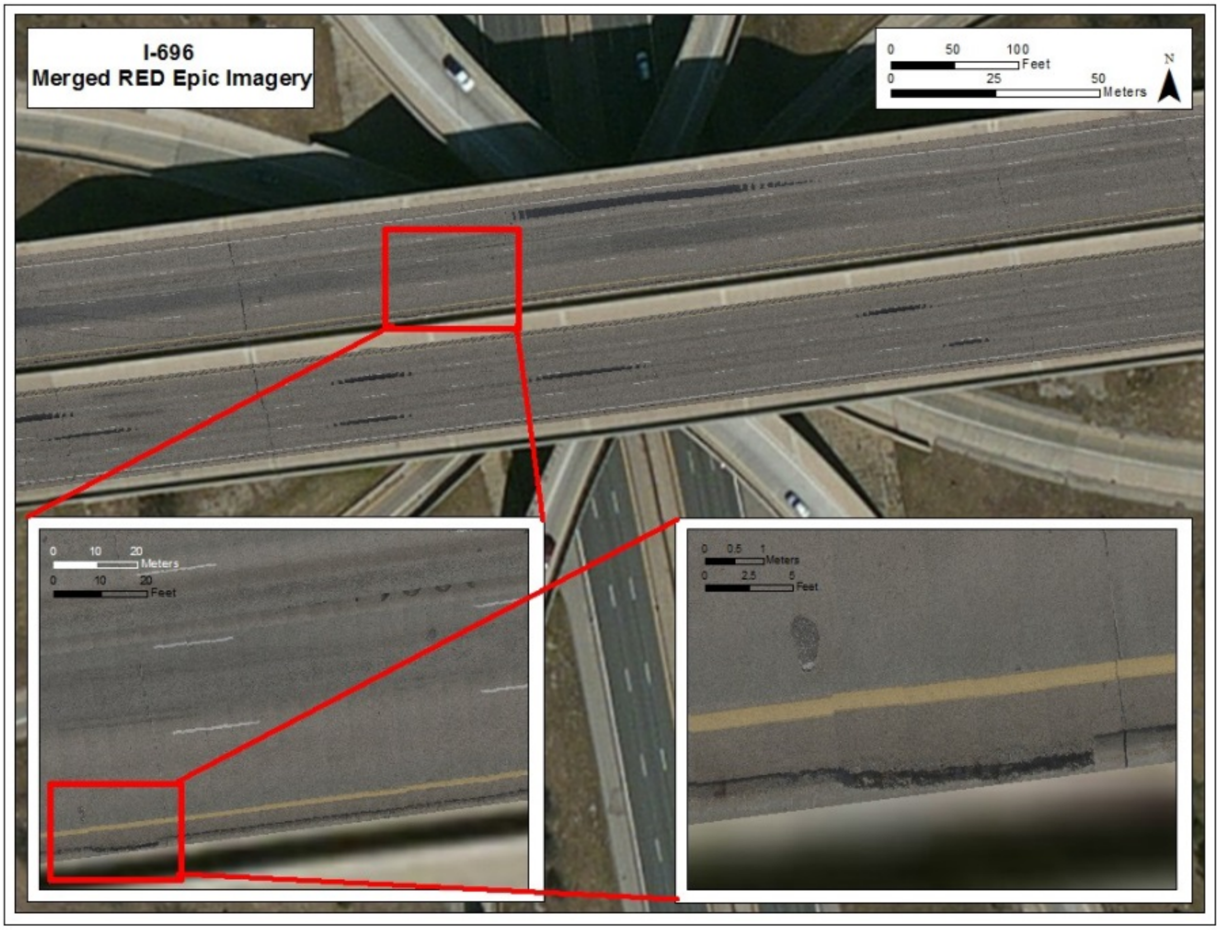


**Figure 32: RED Epic imagery merged together to form I-696 eastbound and westbound bridge decks.**

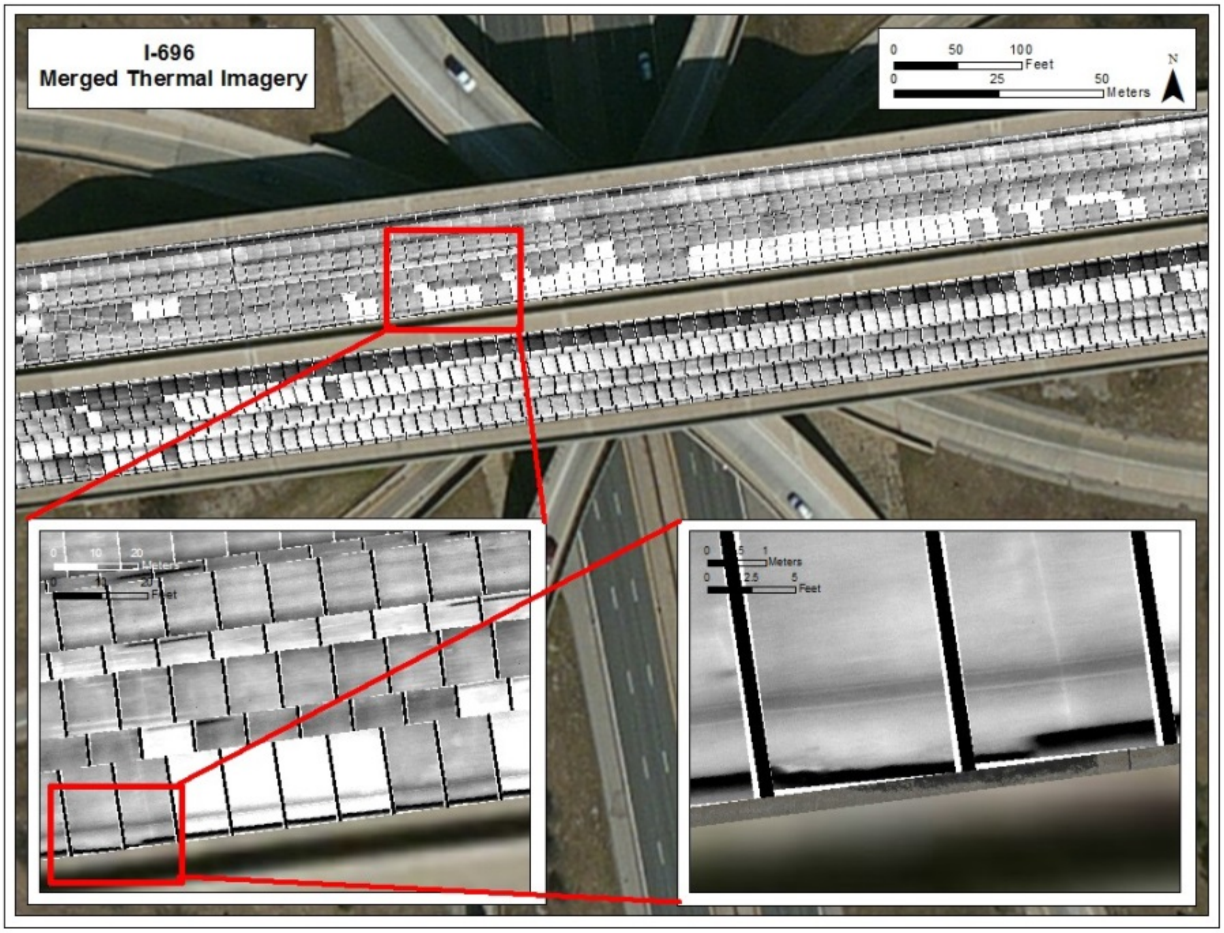


**Figure 33: Merged thermal imagery of the I-696 bridge deck.**

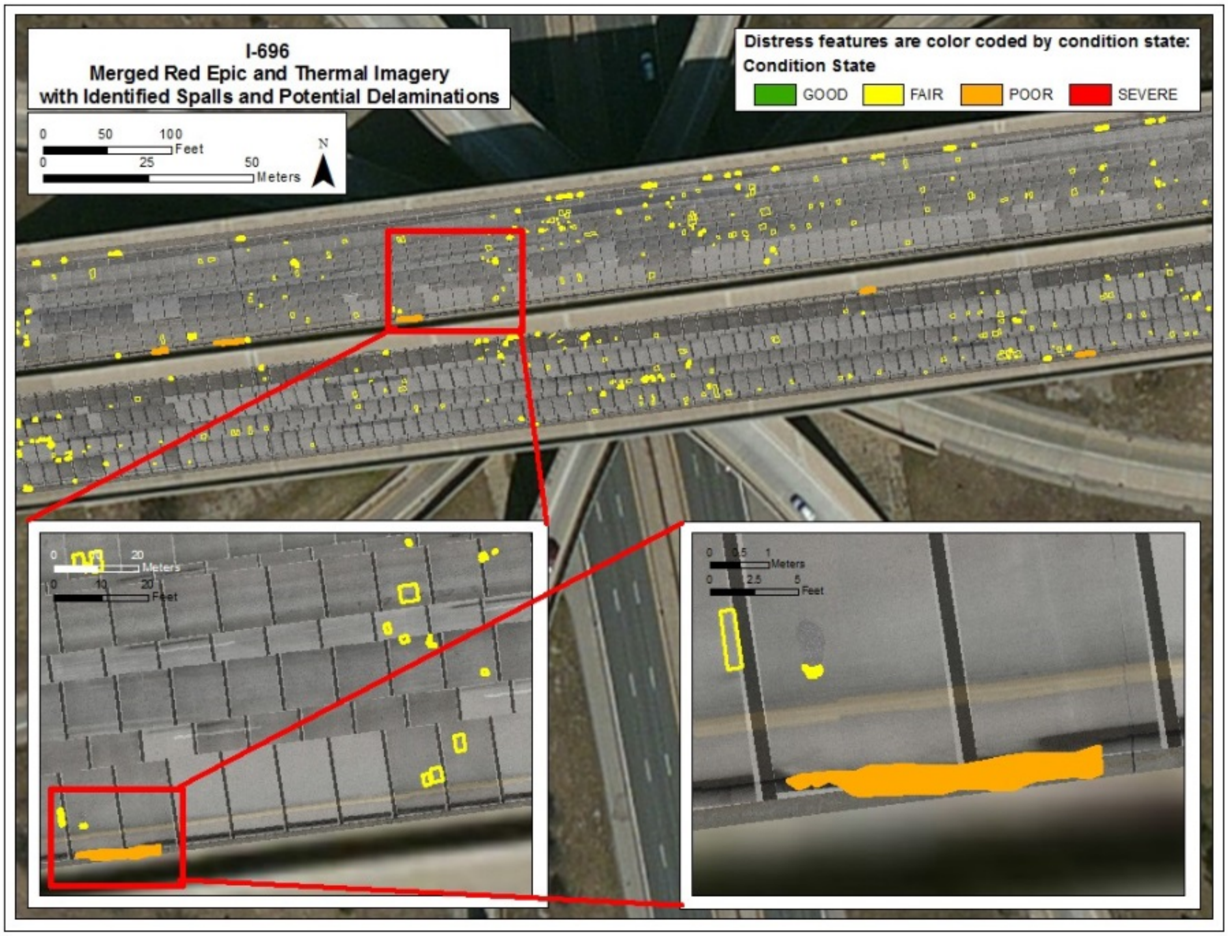


**Figure 34: Location of potential delaminations and spalls on the I-696 bridge deck.**

### 4.3.5 3DOBS Accuracy Assessment

With the ability to process the RED Epic imagery through Agisoft PhotoScan, full models were created of each lane of the Lake Nepessing Rd. bridge deck (StrID: 5330) in Lapeer. Unlike the large deck bridges, the vehicle speed was limited to no more than 10 mph due to the space constraints of the required bridge lane closures. Both the north (Figure 35) and southbound (Figure 36) lanes were processed using the geotagged imagery. Each orthoimage has a resolution of 0.8 mm (~ 1/32 in.) and the DEM has a resolution of 3.2 mm (~1/8 in.). The orthoimage was used to calculate the length and width of each spall and patch while the DEM is used to calculate the depth of the spalls. Also shown in Figures 37 and 38 are hillshade views generated to produce a shadowed 3D image of the DEM through ArcGIS.

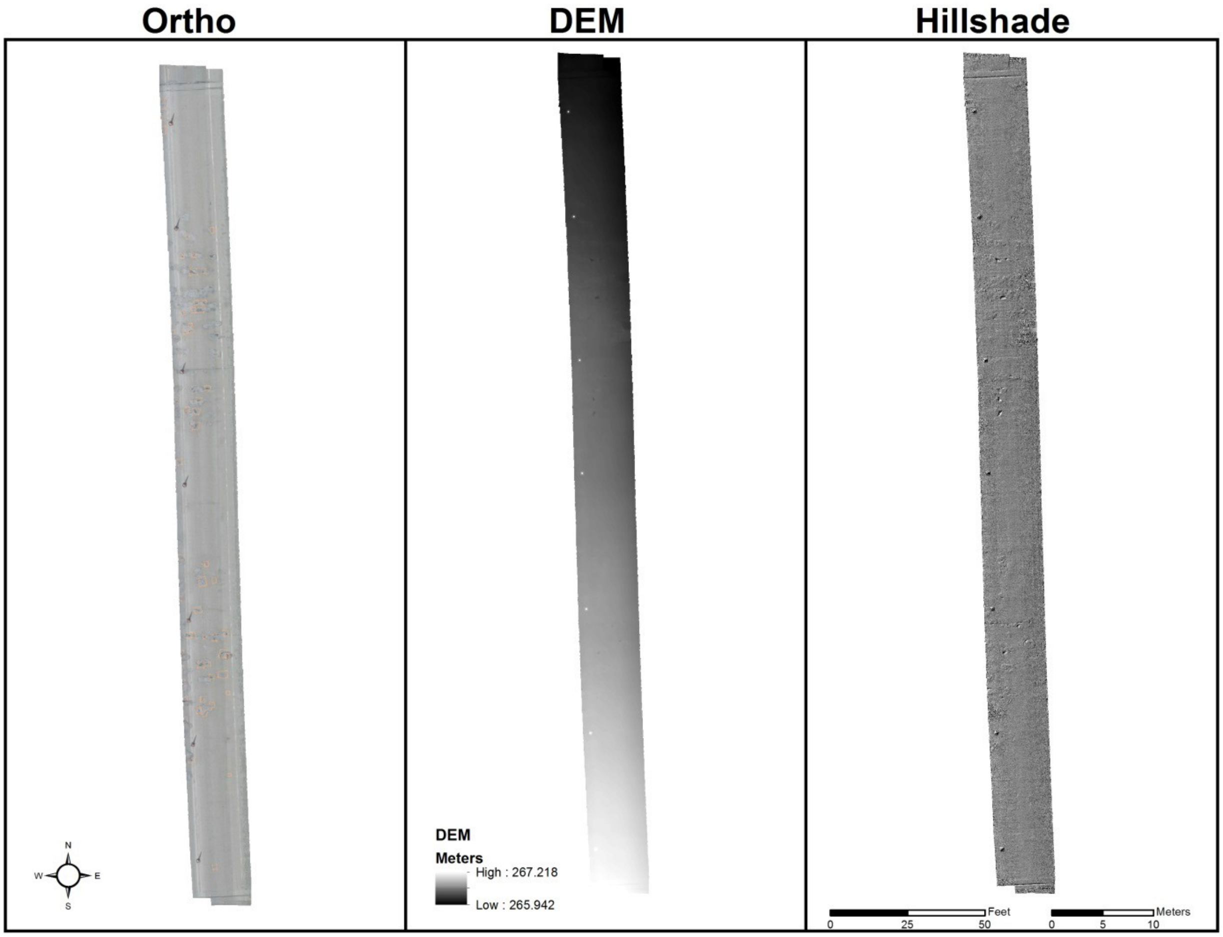


**Figure 35: Final products (Orthoimage, DEM and Hillshade) of the northbound lane of Lake Nepessing Rd. bridge deck.**

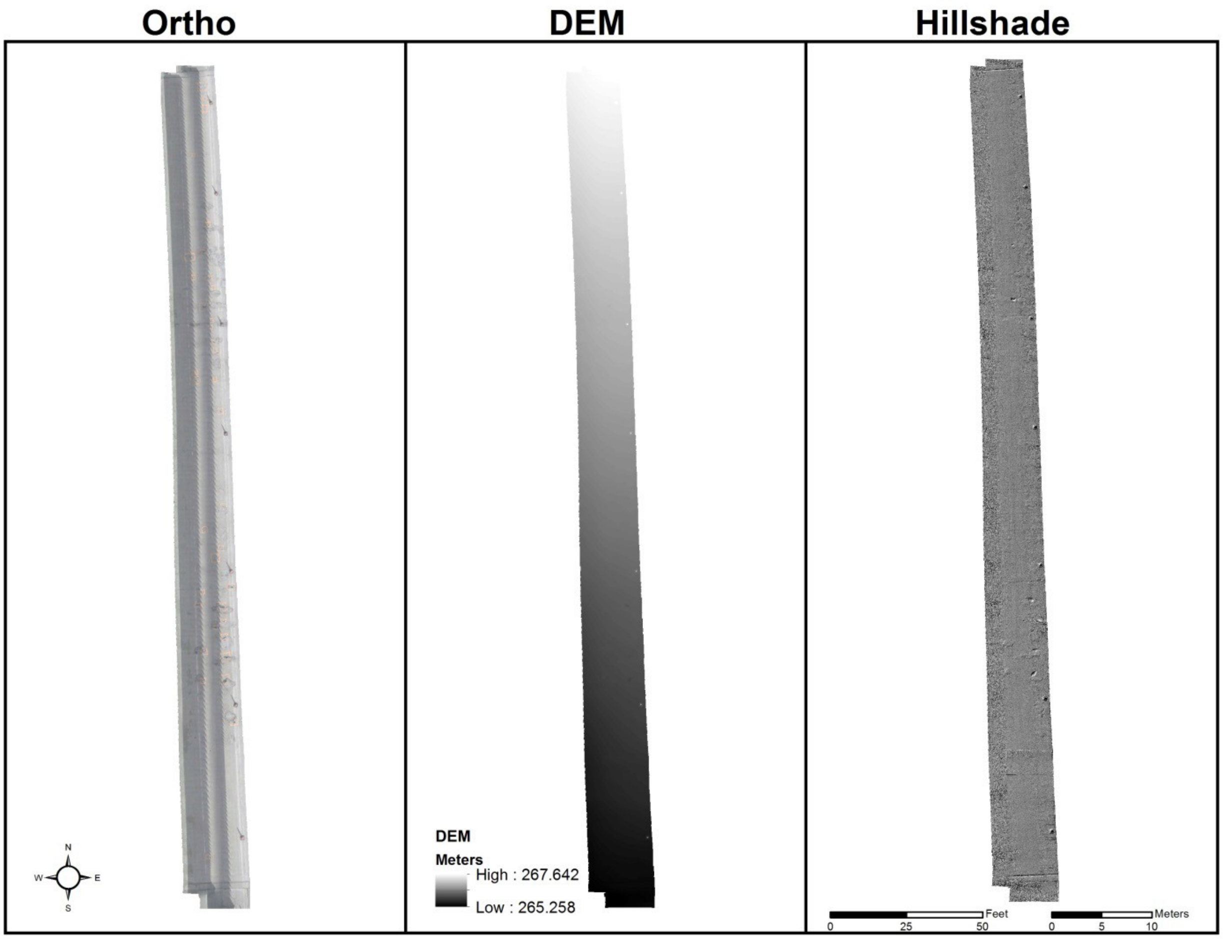


**Figure 36: Final products (Orthoimage, DEM and Hillshade) of the southbound lane of Lake Nepessing Rd. bridge deck.**

Figure 37 shows a zoomed in section of the northbound lane of Lake Nepessing Rd. bridge deck. With a high-resolution orthoimage model, spalls and patches can be located and measured to compare to the in situ measurements. The hillshade of the DEM was reconstructed to show the detail of the patches and spalls (Figure 38). The increased noise on the right and left sides of the hillshade is a result of those areas being mostly flat and with less imagery overlap. There is less overlap on the sides than the center of the model. The edges were reconstructed from a single pass resulting in a point on the ground being represented in five frames. The center of the model was reconstructed from the overlap of both passes of the data collection resulting in a point on the ground being represented in at least 10 frames. The noise in the z-axis, or the amount of random error in the model reconstruction, in the center of the model is 0.16 in. (4.2mm) while on the sides of the model is up to 1.79 in. (4.5cm). Features such as spalls cannot be distinguished if they are less than this error.


**Figure 37: Zoomed in portion of the Orthoimage of northbound Lake Nepessing Rd. bridge deck.**

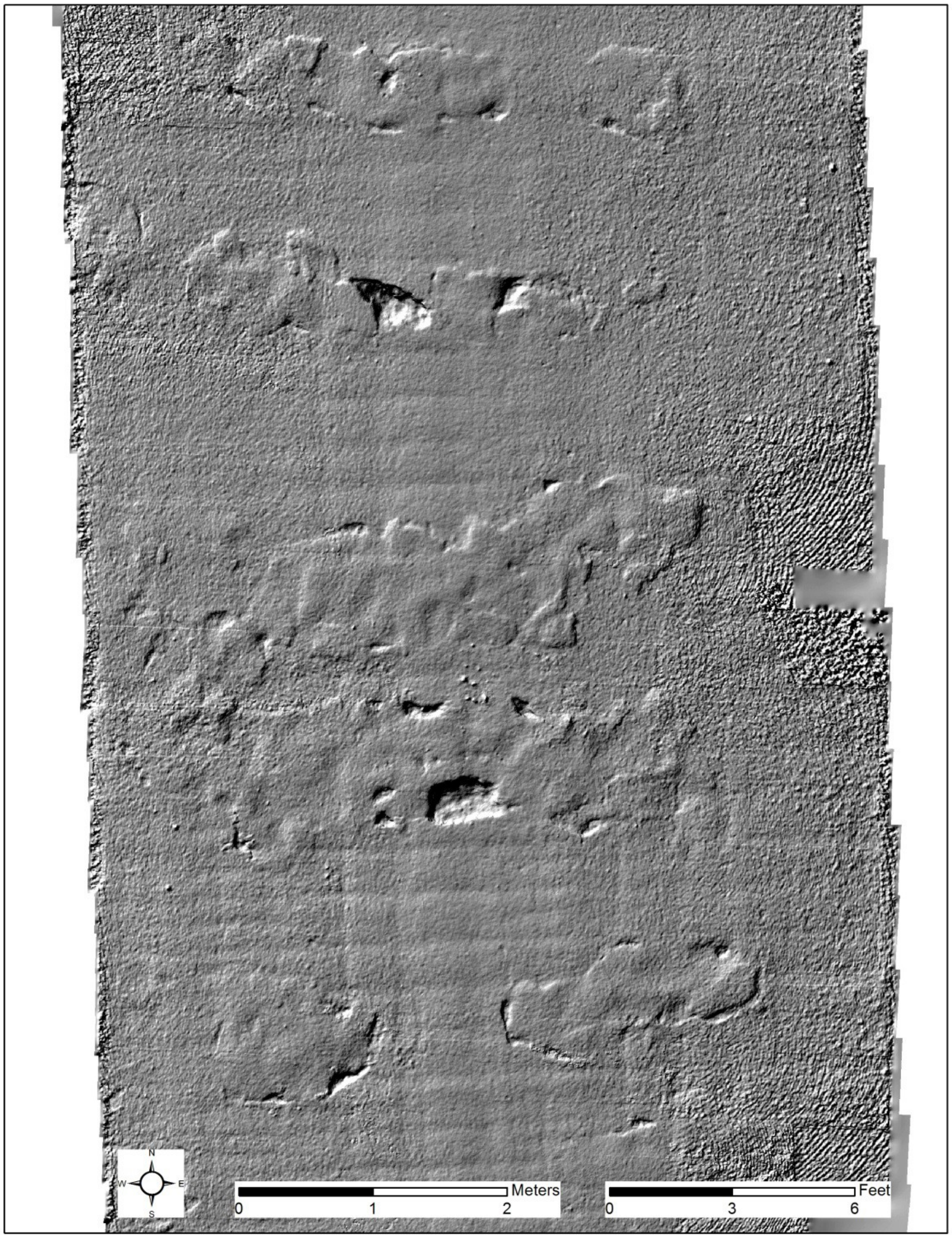


**Figure 38: Zoomed in portion of the Hillshade view of northbound Lake Nepessing Rd. bridge deck.**

Both northbound and southbound lanes were processed through Agisoft PhotoScan using only the geotagged RED Epic imagery. The northbound lane was also processed using ground control markers with the raw un-geotagged RED Epic frames. This was done using eight of the ground control marks placed on the deck prior to the data collection to compare the difference in reconstruction accuracies between using only geotagged imagery and ground control markers. Camera orientation information is not needed for the processing of imagery when using ground control markers as the software determines the model orientation based on the GPS locations of the markers on the model.

This type of DEM output provides MDOT with the ability to gather other types of useful information about a bridge deck as shown in the original USDOT Bridge Condition Remote Sensing project (Ahlborn et al, 2013). International Roughness Index (IRI) data can be extracted from these high resolution DEMs, which in turn can inform MDOT of the overall ride quality of a vehicles as it travels across a bridge. This could be accomplished by extracting elevation values from the DEM along simulated tire tracks digitized within ArcGIS, and evaluating the difference in elevation along the tire track within ProVAL, a software application used for analyzing pavement profiles.

A spall detection algorithm developed under the USDOT/RITA Bridge Condition Assessment Using Remote Sensors project (Ahlborn et al., 2013) was used on the resulting DEMs to create a spalls shapefile for the Lake Nepessing Rd. bridge deck. Figure 39 is an example of the northbound lane of Lake Nepessing Rd with the detected spalls layer. The spalls layer also contains area and volume of the detected spalls. Lake Nepessing Rd bridge deck is estimated to be 80.4 $ft^2$ or about 1% of the bridge deck is spalled based on the detected spalls layer. Of the spalls detected 68% were in Condition State 2 and 32% were in Condition State 3.

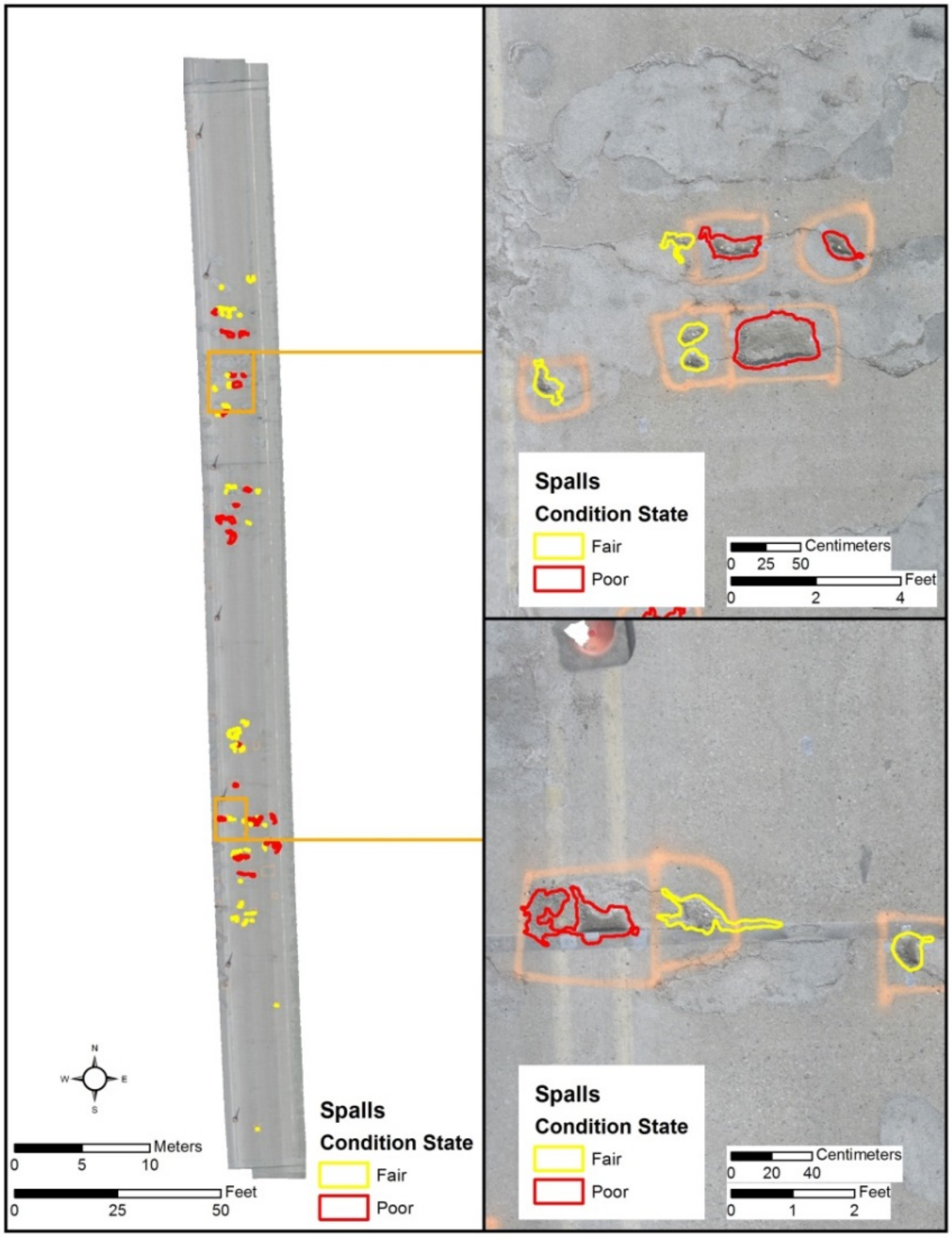


**Figure 39: Northbound Lake Nepessing Rd bridge deck orthoimage with the detected spalls layer showing the location of spalls.**

There were three models made for Lake Nepessing Rd. The first two models, South Geotag and North Geotag, were reconstructed using the geotagged RED imagery. The third model, North Markers, was reconstructed using non-geotagged RED imagery and ground control markers to set the coordinate system and scale the model. Table 6 is a comparison of field measurements to model measurements for the North Markers model. In the “Diff” column a positive number indicates the model estimated the feature to be larger than in situ measurements and a negative number indicates the model estimated the feature to be smaller than in situ measurements.

**Table 6: Comparison of the measurements taken of distress features on from the field and from the Agisoft 3D model using ground control markers.**

| FeatureID | Feature Type | Field Length (in) | Model Length (in) | Diff (in) | Field Width (in) | Model Width (in) | Diff (in) | Field Depth (in) | Model Depth (in) | Depth Diff ( in) |
|---|---|---|---|---|---|---|---|---|---|---|
| JS11 | Spall | 9.50 | 9.47 | 0.03 | 6.00 | 5.96 | 0.04 | 0.75 | 0.52 | 0.23 |
| JS13 | Spall | 9.25 | 9.29 | 0.04 | 8.25 | 8.21 | 0.04 | 1.00 | 0.36 | 0.64 |
| JS21 | Spall | 6.50 | 6.48 | 0.02 | 2.50 | 2.46 | 0.04 | 0.50 | 0.20 | 0.30 |
| JS22 | Spall | 3.50 | 2.78 | 0.72 | 2.00 | 2.15 | 0.15 | 0.50 | 0.26 | 0.24 |
| JS23 | Patch | 23.50 | 23.33 | 0.17 | 13.00 | 13.02 | 0.02 | **N/A** | **N/A** | **N/A** |
| JS24 | Spall | 14.00 | 13.76 | 0.24 | 6.00 | 5.95 | 0.05 | 1.25 | 1.03 | 0.22 |
| JS25 | Spall | 18.50 | 18.31 | 0.19 | 10.25 | 10.37 | 0.12 | 1.50 | 1.11 | 0.39 |
| JS26 | Spall | 13.25 | 13.25 | 0.00 | 4.00 | 4.00 | 0.00 | 1.00 | 0.79 | 0.21 |
| JS27 | Spall | 16.00 | 15.85 | 0.15 | 5.50 | 5.35 | 0.15 | 2.25 | 1.73 | 0.52 |
| JS28 | Spall | 11.75 | 11.65 | 0.10 | 5.25 | 5.27 | 0.02 | 1.25 | 0.84 | 0.41 |
| JS29 | Spall | 13.50 | 13.51 | 0.01 | 7.50 | 7.46 | 0.04 | 1.75 | 0.88 | 0.87 |
| JS30 | Spall | 16.50 | 16.44 | 0.06 | 10.50 | 10.59 | 0.09 | 1.50 | 0.21 | 1.29 |
| JS31 | Spall | 6.25 | 6.24 | 0.01 | 4.50 | 4.48 | 0.02 | 1.50 | 0.59 | 0.91 |
| JS32 | Spall | 12.25 | 12.16 | 0.09 | 4.50 | 4.59 | 0.09 | 1.00 | 0.94 | 0.06 |
| JS33 | Spall | 17.00 | 16.90 | 0.10 | 6.00 | 6.01 | 0.01 | 1.50 | 1.59 | 0.09 |
| JS34 | Spall | 13.75 | 13.71 | 0.04 | 4.00 | 3.99 | 0.01 | 2.00 | 1.01 | 0.99 |
| JS35 | Spall | 5.00 | 5.00 | 0.00 | 2.50 | 2.77 | 0.27 | 0.50 | 0.54 | 0.04 |
| JS36 | Spall | 8.50 | 8.30 | 0.20 | 2.25 | 2.27 | 0.02 | 1.00 | 0.64 | 0.36 |
| JS37 | Spall | 8.25 | 8.23 | 0.02 | 3.75 | 3.54 | 0.21 | 1.00 | 0.71 | 0.29 |
| JS38 | Spall | 5.50 | 5.50 | 0.00 | 3.25 | 3.29 | 0.04 | 1.25 | 0.79 | 0.46 |
| JS39 | Spall | 20.00 | 19.83 | 0.17 | 12.50 | 12.44 | 0.06 | 1.75 | 1.66 | 0.09 |
| JS40 | Spall | 13.00 | 12.84 | 0.16 | 4.50 | 4.50 | 0.00 | 1.00 | 0.81 | 0.19 |
| JS41 | Spall | 10.75 | 10.16 | 0.59 | 4.50 | 4.45 | 0.05 | 1.25 | 0.83 | 0.42 |
| LN12 | Spall | 9.53 | 9.59 | 0.06 | 4.84 | 4.85 | 0.01 | 1.02 | 0.56 | 0.46 |
| LN23 | Spall | 4.80 | 4.75 | 0.05 | 3.82 | 3.80 | 0.02 | 0.55 | 0.29 | 0.26 |
| LN24 | Spall | 15.00 | 16.93 | 1.93 | 2.72 | 2.68 | 0.04 | 0.98 | 0.78 | 0.20 |
| LN25 | Spall | 10.87 | 10.75 | 0.12 | 2.83 | 2.79 | 0.04 | 0.98 | 0.61 | 0.37 |
| LN26 | Spall | 6.81 | 6.88 | 0.07 | 2.48 | 2.36 | 0.12 | 0.71 | 0.45 | 0.26 |
| LN28 | Spall | 19.13 | 19.19 | 0.06 | 7.87 | 7.88 | 0.01 | 0.75 | 0.69 | 0.06 |
| LN29 | Spall | 4.02 | 4.10 | 0.08 | 2.56 | 2.59 | 0.03 | 0.43 | 0.19 | 0.24 |
| LN30 | Spall | 3.98 | 3.90 | 0.08 | 3.74 | 3.70 | 0.04 | 0.79 | 0.48 | 0.31 |
| LN31 | Spall | 7.01 | 7.01 | 0.00 | 3.74 | 3.83 | 0.09 | 0.75 | 0.44 | 0.31 |
| LN32 | Spall | 7.56 | 7.54 | 0.02 | 2.24 | 2.19 | 0.05 | 0.51 | 0.43 | 0.08 |
| LN33 | Spall | 5.98 | 5.91 | 0.07 | 4.41 | 4.43 | 0.02 | 0.63 | 0.47 | 0.16 |
| LN34 | Spall | 28.58 | 28.41 | 0.17 | 12.01 | 11.79 | 0.22 | 1.77 | 1.70 | 0.07 |
| LN35 | Spall | 20.91 | 20.50 | 0.41 | 11.06 | 10.90 | 0.16 | 1.89 | 1.80 | 0.09 |
| LN36 | Spall | 7.76 | 7.49 | 0.27 | 3.35 | 3.36 | 0.01 | 0.87 | 0.50 | 0.37 |
| LN37 | Spall | 7.72 | 7.77 | 0.05 | 4.53 | 4.52 | 0.01 | 1.06 | 0.77 | 0.29 |
| LN38 | Spall | 9.76 | 9.80 | 0.04 | 3.70 | 3.65 | 0.05 | 0.79 | 0.51 | 0.28 |
| LN39 | Spall | 6.69 | 6.69 | 0.00 | 4.09 | 4.09 | 0.00 | 0.71 | 0.66 | 0.05 |
| LN40 | Spall | 8.35 | 8.39 | 0.04 | 3.54 | 3.59 | 0.05 | 1.06 | 0.57 | 0.49 |
| LN41 | Spall | 26.38 | 26.06 | 0.32 | 12.91 | 12.86 | 0.05 | 1.85 | 1.75 | 0.10 |
| LN42 | Spall | 12.68 | 12.43 | 0.25 | 8.50 | 8.47 | 0.03 | 1.10 | 1.02 | 0.08 |

Table 7 shows summary statistics for each of the three models generated for Lake Nepessing Rd. There were 31 spalls and 7 patches measured on the southbound lanes and 42 spalls and 1 patch measured on the northbound lanes. The values used for these statistics are the absolute values of the difference values shown in Table 6. This is to show the absolute difference between the field measurements and the model reconstruction and to calculate the coefficient of variation which requires only positive values.

**Table 7: Comparison of spall measurements taken from the field and from the 3D model generated from the RED Epic imagery.**

| Markers North | | | | |
|---|---|---|---|---|
| **XY Error** | | | **Z Error** | |
| Average (in) | 0.11 | | Average (in) | 0.33 |
| Min (in) | 0.00 | | Min (in) | 0.04 |
| Max (in) | 1.93 | | Max (in) | 1.29 |
| St Dev (in) | 0.23 | | St Dev (in) | 0.27 |
| Coeff of Variation | 2.04 | | Coeff of Variation | 0.84 |
| **GPS North** | | | | |
| **XY Error** | | | **Z Error** | |
| Average (in) | 0.16 | | Average (in) | 0.32 |
| Min (in) | 0.00 | | Min (in) | 0.01 |
| Max (in) | 1.47 | | Max (in) | 1.12 |
| St Dev (in) | 0.22 | | St Dev (in) | 0.25 |
| Coeff of Variation | 1.36 | | Coeff of Variation | 0.76 |
| **GPS South** | | | | |
| **XY Error** | | | **Z Error** | |
| Average (in) | 0.33 | | Average (in) | 0.29 |
| Min (in) | 0.00 | | Min (in) | 0.00 |
| Max (in) | 2.34 | | Max (in) | 0.74 |
| St Dev (in) | 0.42 | | St Dev (in) | 0.19 |
| Coeff of Variation | 1.29 | | Coeff of Variation | 0.67 |

### 4.3.6 Span Condition Ratings

As part of determining the overall condition of a bridge deck through the use of remote sensing techniques, MDOT requested that in addition to the mapping of potential spalls and delaminations, quantitative values of each bridge condition distress be broken down by bridge span, condition state, and entire bridge deck. The different condition states for each type of bridge distress are based on MDOT's Michigan Bridge Element Inspection Manual (MDOT, 2015) and are as follows:

- Condition State 1 – Good: the span cannot contain any spall or delamination distress feature.
- Condition State 2 – Fair: the span would contain the presence of a delamination or a spall that is one inch or less in depth or less than six inches in diameter.
- Condition State 3 – Poor: the bridge span must contain a spall that is greater than one inch deep or greater than six inches in diameter and the span cannot warrant structural review.
- Condition State 4 – Severe: the span condition must warrant structural review to determine strength or serviceability capacity.

Using MDOT's Bridge Safety Inspection Reports retrieved from the MiBridge website, the number of approach and main spans were determined. Based on these numbers and imagery of each bridge, the location of each bridge span was determined. The 8 Mile Bridge did not contain any spalls, and therefore the condition state of each span was based on the presence or absence of a delamination. All 15 spans (3 main spans and 12 approach spans) of the bridge contained the presence of at least one delamination. Through GIS analysis, the total bridge deck area was calculated to be 167,660 $ft^2$. The total delaminated area as reported through digitization and georeferencing of thermal infrared digital imagery was calculated to be 3,092 $ft^2$, or 1.84% of the total bridge deck. This also indicates that 3,092 $ft^2$ (1.84%) of the total bridge deck falls under Condition State 2 – Fair. As there were no reported spalls on the bridge deck, the remaining 164,568 $ft^2$ (98.16%) of bridge deck is classified as Condition State 1 – Good (Table 8 and Figure 40). The spans with the greatest and least area of delaminations are span 8 and span 12, respectively. For the location of individual distress features, please reference Figure 25 in Section 4.3.1.

**Table 8: Area of Condition States per span for the M-102 (8 Mile) bridge deck.**

| Location: M- 102 (8 Mile) | Area of Span ($ft^2$) | Area Cond. State 1 ($ft^2$) GOOD | Area Cond. State 2 ($ft^2$) FAIR | Area Cond. State 3 ($ft^2$) POOR | Area Cond. State 4 ($ft^2$) SEVERE |
|---|---|---|---|---|---|
| Span 1 | 8,221 | 8,093 | 128 | 0 | 0 |
| Span 2 | 8,217 | 7,997 | 220 | 0 | 0 |
| Span 3 | 8,646 | 8,481 | 165 | 0 | 0 |
| Span 4 | 11,552 | 11,434 | 118 | 0 | 0 |
| Span 5 | 11,521 | 11,340 | 181 | 0 | 0 |
| Span 6 | 11,502 | 11,280 | 222 | 0 | 0 |
| Span 7 | 19,525 | 19,114 | 411 | 0 | 0 |
| Span 8 | 11,540 | 11,117 | 423 | 0 | 0 |
| Span 9 | 8,593 | 8,441 | 152 | 0 | 0 |
| Span 10 | 11,855 | 11,663 | 192 | 0 | 0 |
| Span 11 | 11,798 | 11,511 | 287 | 0 | 0 |
| Span 12 | 11,887 | 11,824 | 63 | 0 | 0 |
| Span 13 | 12,861 | 12,598 | 263 | 0 | 0 |
| Span 14 | 9,996 | 9,860 | 136 | 0 | 0 |
| Span 15 | 9,945 | 9,814 | 131 | 0 | 0 |
| **Total** | **167,660** | **164,568** | **3,092** | **0.00** | **0.00** |
| | | **(98.16%)** | **(1.84%)** | **(0%)** | **(0%)** |

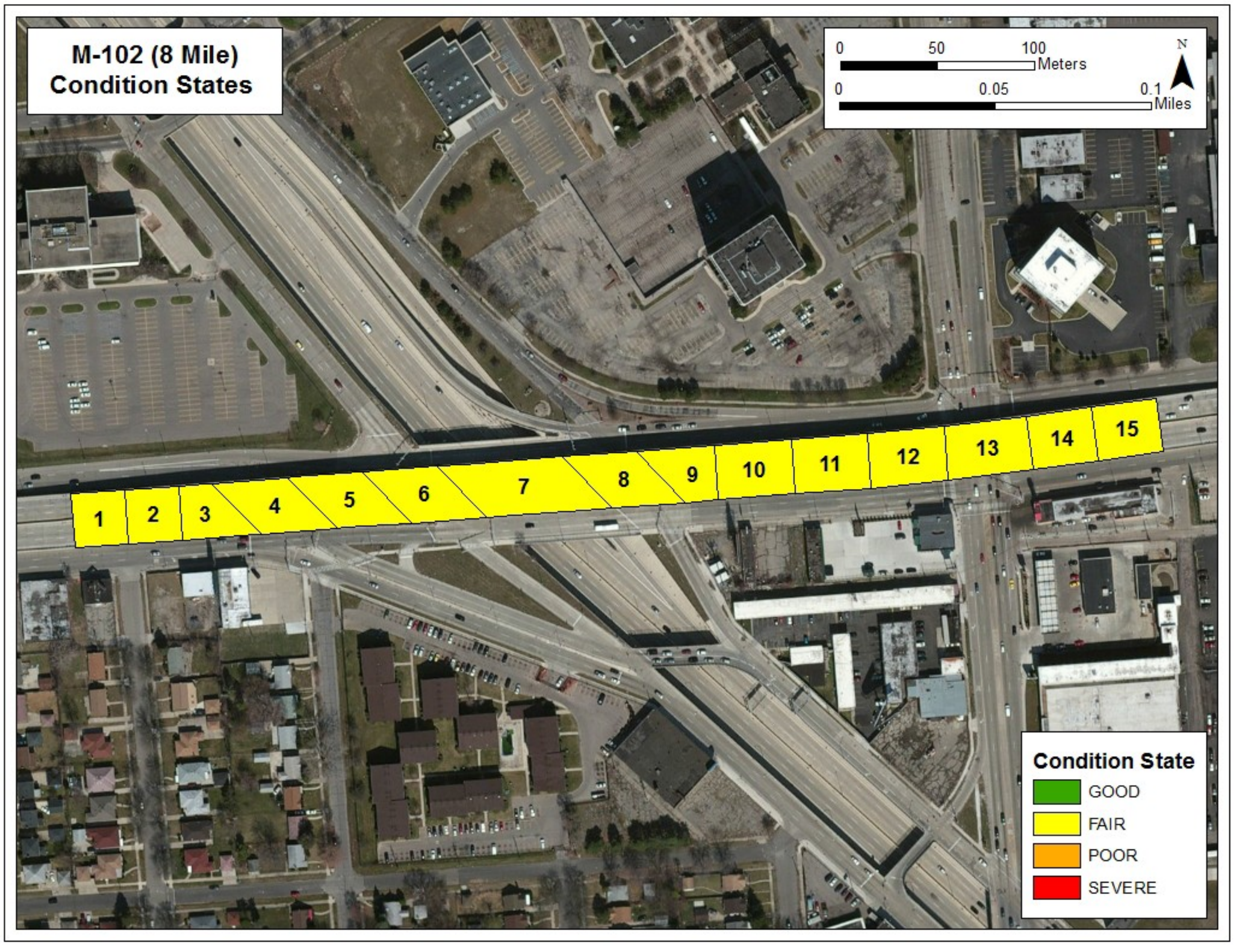


**Figure 40: Summary of Condition state per span at M-102 (8 Mile).**

The US-131 northbound bridge contained 24 spalls and 37 delaminations within the defined 9 spans of the bridge deck (9 main spans and 0 approach spans). Through GIS analysis, the total bridge deck area was calculated to be 115,926 $ft^2$. The total area of Condition State 2 – Fair distress features was determined to be 168 $ft^2$, or approximately 0.15% of the total bridge deck (168 $ft^2$ classified as delaminations and 0.35 $ft^2$ classified as spalls that are 6 inches or less in diameter). Likewise, the total area of Condition State 3 – Poor distress features was determined to be 0.23 $ft^2$, or approximately 0% of the total bridge deck (consisting of only spalls that are greater than 6 inches in diameter because delaminations are always classified as Condition State 2). The remainder of the bridge deck not containing spalls or delaminations was classified as Condition State 1 – Good and equates to 115,757 $ft^2$, or approximately 99.85% (Table 9 and Figure 41). For the location of individual distress features, please reference Figure 28 in Section 4.3.2.

**Table 9: Area of condition state per span for the US-131 northbound bridge deck.**

| Location: US131 | Area of Span (ft²) | Area Cond. State 1 (ft²) GOOD | Area Cond. State 2 (ft²) FAIR | Area Cond. State 3 (ft²) POOR | Area Cond. State 4 (ft²) SEVERE |
|---|---|---|---|---|---|
| Span 1 | 7,642 | 7,629 | 13 | 0 | 0 |
| Span 2 | 9,318 | 9,299 | 19 | 0 | 0 |
| Span 3 | 15,456 | 15,451 | 5 | 0 | 0 |
| Span 4 | 14,872 | 14,865 | 7 | 0 | 0 |
| Span 5 | 15,120 | 15,105 | 15 | 0 | 0 |
| Span 6 | 13,711 | 13,675 | 36 | 0 | 0 |
| Span 7 | 15,524 | 15,489 | 35 | 0 | 0 |
| Span 8 | 12,647 | 12,643 | 4 | 0 | 0 |
| Span 9 | 11,635 | 11,601 | 34 | 0 | 0 |
| **Total** | **115,926** | **115,757** | **168** | **0** | **0** |
| | | **(99.85%)** | **(0.15%)** | **(0%)** | **(0%)** |

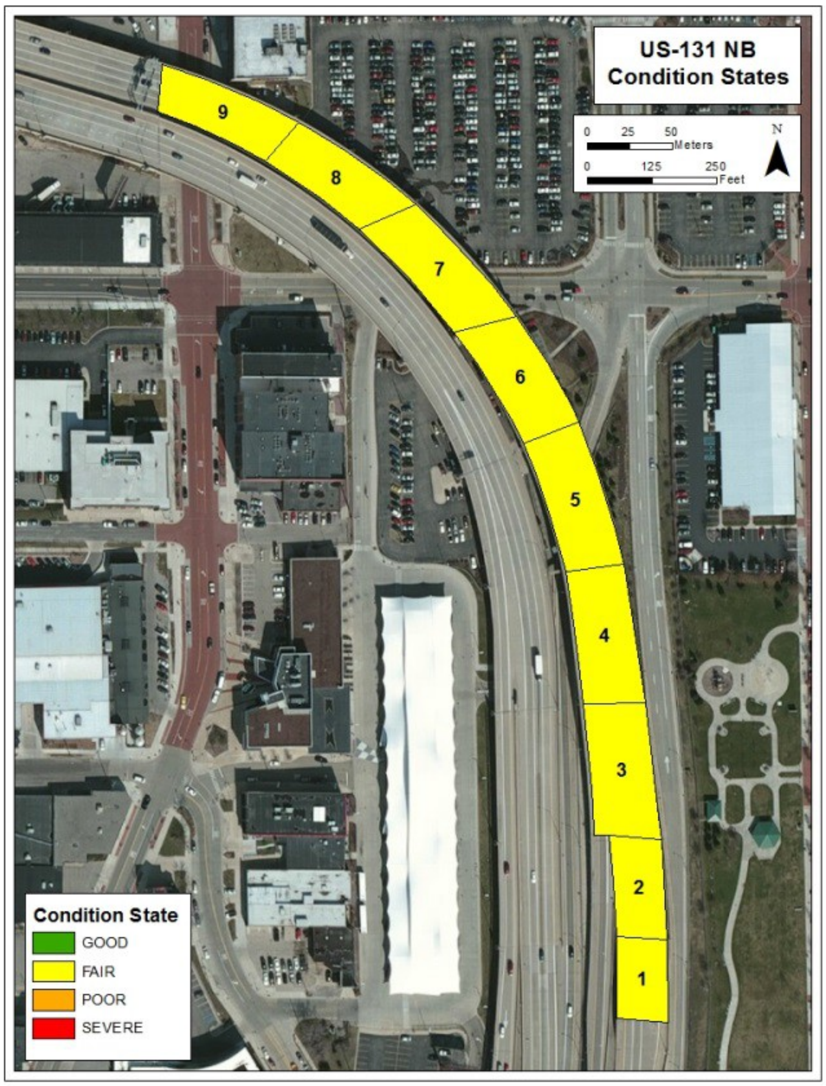


**Figure 41: Summary of condition state per span at US-131 northbound.**

The US-131 southbound bridge contained 1 spall and 96 delaminations within the defined 8 spans of the bridge deck (8 main spans and 0 approach spans). Through GIS analysis, the total bridge deck area was calculated to be 98,090 $ft^2$. The total area of Condition State 2 – Fair distress features was determined to be 364 $ft^2$, or approximately 0.37% of the total bridge deck (364 $ft^2$ classified as delaminations and 0.07 $ft^2$ as spalling). The remainder of the bridge deck not containing spalls or delaminations was classified as Condition State 1 – Good and equates to 97,726 $ft^2$, or approximately 99.63% (Table 10 and Figure 42). For the location of individual distress features, please reference Figure 28 in Section 4.3.2.

**Table 10: Area of condition state per span for the US-131 southbound bridge deck.**

| Location: US131 | Area of Span ($ft^2$) | Area Cond. State 1 ($ft^2$) GOOD | Area Cond. State 2 ($ft^2$) FAIR | Area Cond. State 3 ($ft^2$) POOR | Area Cond. State 4 ($ft^2$) SEVERE |
|---|---|---|---|---|---|
| Span 1 | 8,609 | 8,599 | 10 | 0 | 0 |
| Span 2 | 11,378 | 11,317 | 61 | 0 | 0 |
| Span 3 | 16,329 | 16,294 | 35 | 0 | 0 |
| Span 4 | 14,180 | 14,129 | 51 | 0 | 0 |
| Span 5 | 13,327 | 13,253 | 74 | 0 | 0 |
| Span 6 | 13,355 | 13,314 | 41 | 0 | 0 |
| Span 7 | 10,027 | 9,999 | 28 | 0 | 0 |
| Span 8 | 10,887 | 10,823 | 64 | 0 | 0 |
| **Total** | **98,090** | **97,726** | **364** | **0.00** | **0.00** |
| | | **(99.63%)** | **(0.37%)** | **(0%)** | **(0%)** |

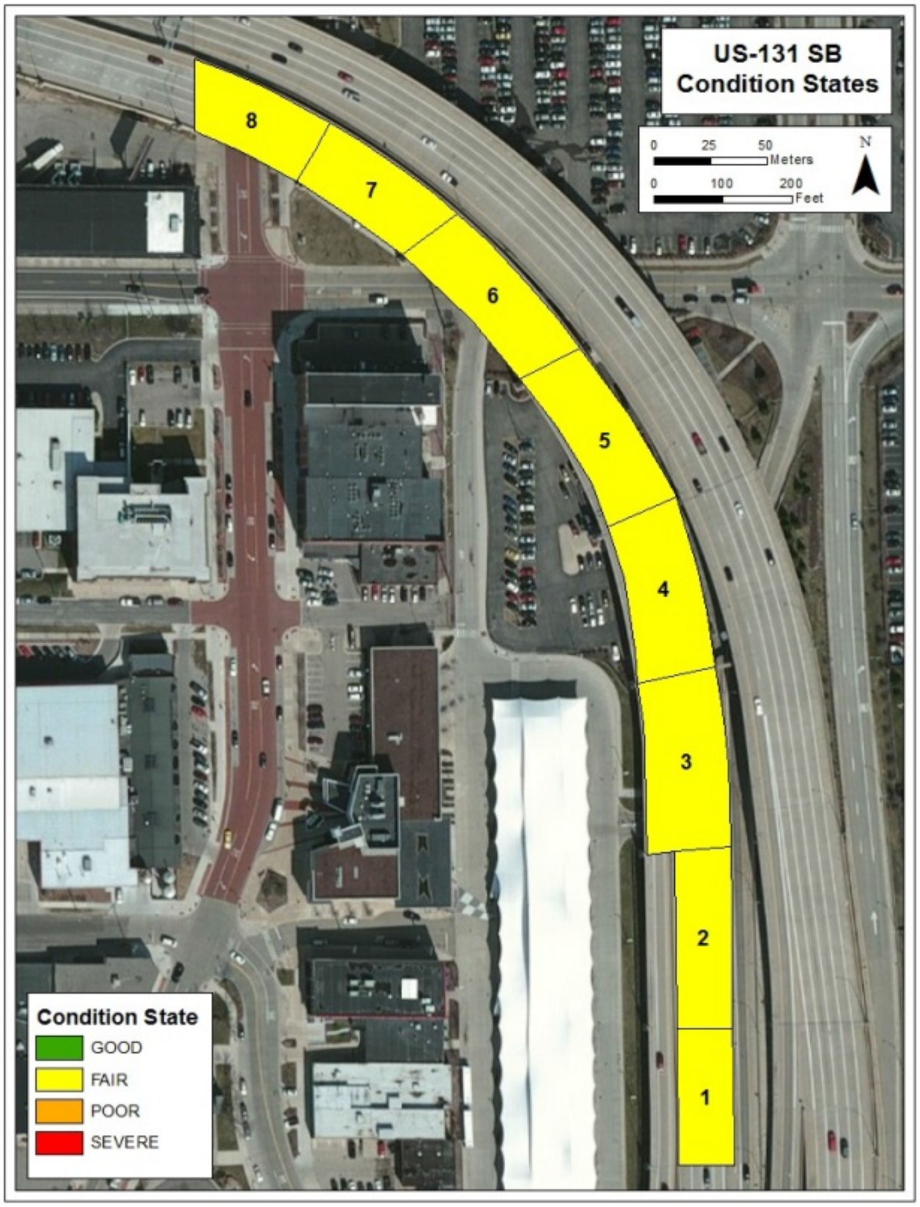


**Figure 42: Summary of condition state per span at US-131 southbound.**

The I-75 northbound bridge contained 227 spalls and 529 delaminations within the defined 32 spans of the bridge deck (27 main spans and 5 approach spans). Through GIS analysis, the total bridge deck area was calculated to be 95,014 $ft^2$. The total area of Condition State 2 – Fair distress features was determined to be 2,211 $ft^2$, or approximately 2.33% of the total bridge deck (2,204 $ft^2$ classified as delaminations and 7 $ft^2$ classified as spalls that are 6 inches or less in diameter). Likewise, the total area of Condition State 3 – Poor distress features was determined to be 28 $ft^2$, or approximately 0.03% of the total bridge deck (consisting of only spalls that are greater than 6 inches in diameter because delaminations are always classified as Condition State 2). The remainder of the bridge deck not containing spalls or delaminations was classified as Condition

State 1 – Good and equates to 92,776 $ft^2$, or approximately 97.64% (Table 11 and Figure 43). For the location of individual distress features, please reference Figure 31 in Section 4.3.3.

**Table 11: Area of condition states per span for the I-75 northbound bridge deck.**

| Location: I75 NB | Area of Span ($ft^2$) | Area Cond. State 1 ($ft^2$) GOOD | Area Cond. State 2 ($ft^2$) FAIR | Area Cond. State 3 ($ft^2$) POOR | Area Cond. State 4 ($ft^2$) SEVERE |
|---|---|---|---|---|---|
| Span 1 | 2,477 | 2,437 | 40 | 0 | 0 |
| Span 2 | 3,949 | 3,872 | 76 | 1 | 0 |
| Span 3 | 2,287 | 2,023 | 264 | 1 | 0 |
| Span 4 | 2,657 | 2,598 | 58 | 0 | 0 |
| Span 5 | 2,948 | 2,857 | 92 | 0 | 0 |
| Span 6 | 2,905 | 2,857 | 48 | 0 | 0 |
| Span 7 | 2,975 | 2,899 | 75 | 0 | 0 |
| Span 8 | 2,926 | 2,843 | 84 | 0 | 0 |
| Span 9 | 2,963 | 2,900 | 63 | 0 | 0 |
| Span 10 | 2,945 | 2,855 | 89 | 0 | 0 |
| Span 11 | 2,906 | 2,777 | 127 | 2 | 0 |
| Span 12 | 2,913 | 2,824 | 89 | 1 | 0 |
| Span 13 | 2,884 | 2,785 | 97 | 2 | 0 |
| Span 14 | 2,929 | 2,869 | 60 | 0 | 0 |
| Span 15 | 2,959 | 2,878 | 77 | 4 | 0 |
| Span 16 | 2,925 | 2,835 | 87 | 3 | 0 |
| Span 17 | 3,070 | 2,979 | 92 | 0 | 0 |
| Span 18 | 3,945 | 3,799 | 144 | 2 | 0 |
| Span 19 | 2,986 | 2,953 | 33 | 0 | 0 |
| Span 20 | 2,925 | 2,887 | 38 | 0 | 0 |
| Span 21 | 2,981 | 2,958 | 23 | 0 | 0 |
| Span 22 | 2,891 | 2,869 | 22 | 0 | 0 |
| Span 23 | 3,006 | 2,972 | 34 | 0 | 0 |
| Span 24 | 2,977 | 2,933 | 43 | 0 | 0 |
| Span 25 | 2,920 | 2,838 | 82 | 0 | 0 |
| Span 26 | 2,955 | 2,917 | 37 | 1 | 0 |
| Span 27 | 3,038 | 2,987 | 48 | 4 | 0 |
| Span 28 | 2,989 | 2,923 | 60 | 5 | 0 |
| Span 29 | 2,936 | 2,895 | 41 | 0 | 0 |
| Span 30 | 2,992 | 2,963 | 29 | 0 | 0 |
| Span 31 | 2,941 | 2,910 | 31 | 0 | 0 |
| Span 32 | 2,914 | 2,885 | 29 | 0 | 0 |
| **Total** | **95,014** | **92,776** | **2,211** | **28** | **0** |
| | | **(97.64%)** | **(2.33%)** | **(0.03%)** | **(0%)** |

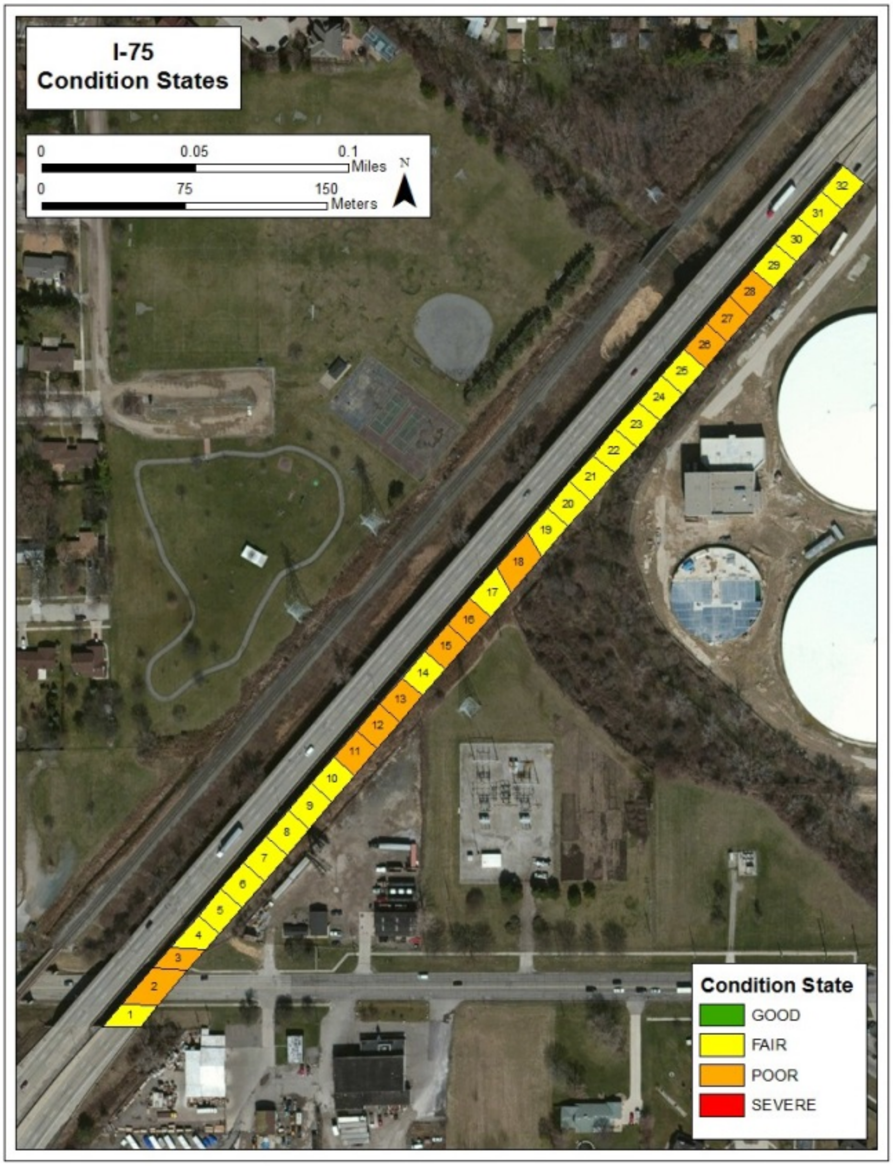


**Figure 43: Summary of condition state per deck span at I-75 northbound.**

The I-75 southbound bridge contained 905 spalls and 1,410 delaminations within the defined 33 spans of the bridge deck (6 main spans and 27 approach spans). Through GIS analysis, the total bridge deck area was calculated to be 97,401 $ft^2$. The total area of Condition State 2 – Fair distress features was determined to be 14,139 $ft^2$, or approximately 14.52% of the total bridge deck (14,119 $ft^2$ classified as delaminations and 20 $ft^2$ classified as spalls that are 6 inches or less in diameter). Likewise, the total area of Condition State 3 – Poor distress features was determined to be 44 $ft^2$, or approximately 0.04% of the total bridge deck (consisting of only spalls that are greater than 6 inches in diameter because delaminations are always classified as Condition State 2). The remainder of the bridge deck that did not contain any spalls or delaminations was classified as Condition State 1 – Good and equated to 83,219 $ft^2$, or approximately 85.44% (Table 12 and Figure 44). For the location of individual distress features, please reference Figure 31 in Section 4.3.3.

**Table 12: Area of condition state per span for the I-75 southbound bridge deck.**

| Location: I -75 SB | Area of Span (ft²) | Area Cond. State 1 (ft²) GOOD | Area Cond. State 2 (ft²) FAIR | Area Cond. State 3 (ft²) POOR | Area Cond. State 4 (ft²) SEVERE |
|---|---|---|---|---|---|
| Span 1 | 2,321 | 2,268 | 52 | 1 | 0 |
| Span 2 | 3,965 | 3,114 | 849 | 3 | 0 |
| Span 3 | 2,430 | 1,928 | 500 | 3 | 0 |
| Span 4 | 2,610 | 1,661 | 948 | 1 | 0 |
| Span 5 | 2,601 | 2,127 | 473 | 0 | 0 |
| Span 6 | 2,918 | 2,147 | 771 | 1 | 0 |
| Span 7 | 2,940 | 2,181 | 759 | 1 | 0 |
| Span 8 | 2,917 | 2,265 | 651 | 1 | 0 |
| Span 9 | 2,884 | 2,378 | 504 | 1 | 0 |
| Span 10 | 2,918 | 2,235 | 682 | 1 | 0 |
| Span 11 | 2,871 | 2,353 | 517 | 1 | 0 |
| Span 12 | 2,969 | 2,711 | 257 | 1 | 0 |
| Span 13 | 2,935 | 2,797 | 137 | 1 | 0 |
| Span 14 | 2,936 | 2,580 | 357 | 0 | 0 |
| Span 15 | 2,938 | 2,694 | 243 | 1 | 0 |
| Span 16 | 2,917 | 2,667 | 249 | 1 | 0 |
| Span 17 | 2,946 | 2,807 | 139 | 0 | 0 |
| Span 18 | 2,972 | 2,857 | 114 | 0 | 0 |
| Span 19 | 3,021 | 2,775 | 238 | 8 | 0 |
| Span 20 | 3,810 | 3,262 | 545 | 3 | 0 |
| Span 21 | 2,975 | 2,563 | 412 | 0 | 0 |
| Span 22 | 2,902 | 2,585 | 316 | 1 | 0 |
| Span 23 | 2,900 | 2,418 | 482 | 0 | 0 |
| Span 24 | 2,927 | 2,607 | 319 | 1 | 0 |
| Span 25 | 2,925 | 2,730 | 194 | 1 | 0 |
| Span 26 | 2,910 | 2,558 | 350 | 2 | 0 |
| Span 27 | 2,949 | 2,298 | 648 | 2 | 0 |
| Span 28 | 2,984 | 2,228 | 755 | 1 | 0 |
| Span 29 | 3,020 | 2,399 | 620 | 2 | 0 |
| Span 30 | 3,041 | 2,700 | 340 | 1 | 0 |
| Span 31 | 3,035 | 2,745 | 289 | 1 | 0 |
| Span 32 | 3,018 | 2,876 | 142 | 0 | 0 |
| Span 33 | 2,993 | 2,706 | 287 | 1 | 0 |
| **Total** | **97,401** | **83,219** | **14,139** | **44** | **0** |
|  |  | **(85.44%)** | **(14.52%)** | **(0.04%)** | **(0%)** |

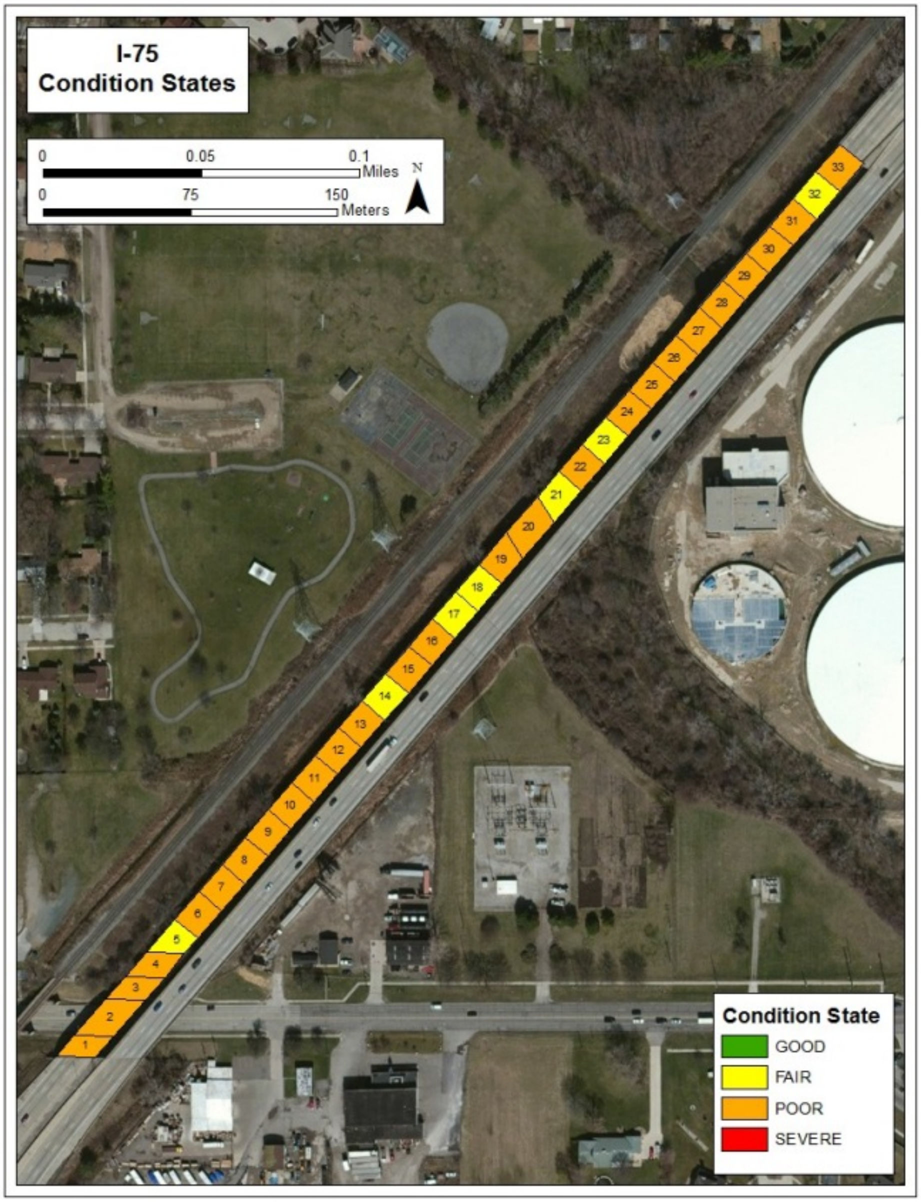


**Figure 44: Summary of condition state per deck span at I-75 southbound.**

The I-696 bridge contained 118 spalls and 261 delaminations within the defined 5 spans of the bridge deck (3 main spans and 2 approach spans). The total area of Condition State 2 – Fair distress features was determined to be 808 $ft^2$, or approximately 0.79% of the total bridge deck (806 $ft^2$ classified as delaminations and 2 $ft^2$ classified as spalls that are 6 inches or less in diameter). Likewise, the total area of Condition State 3 – Poor distress features was determined to be 91 $ft^2$, or approximately 0.08% of the total bridge deck (consisting of only spalls since delaminations are always classified as Condition State 2). The remainder of the bridge deck that did not contain spalls or delaminations was classified as Condition State 1 – Good and equated to 101,309 $ft^2$, or approximately 99.12% (Table 13 and Figure 45). For the location of individual distress features, please reference Figure 34 in Section 4.3.4.

**Table 13: Area of condition state per deck span for the I-696 bridge.**

| Location: I696 / I75 | Area of Span (ft²) | Area Cond. State 1 (ft²) GOOD | Area Cond. State 2 (ft²) FAIR | Area Cond. State 3 (ft²) POOR | Area Cond. State 4 (ft²) SEVERE |
|---|---|---|---|---|---|
| Span 1 | 17,541 | 17,428 | 84 | 29 | 0 |
| Span 2 | 21,329 | 21,214 | 99 | 16 | 0 |
| Span 3 | 24,463 | 24,154 | 285 | 24 | 0 |
| Span 4 | 21,511 | 21,277 | 225 | 9 | 0 |
| Span 5 | 17,363 | 17,237 | 114 | 13 | 0 |
| **Total** | **102,207** | **101,309** | **808** | **91** | **0** |
| | | **(99.12%)** | **(0.79%)** | **(0.09%)** | **(0%)** |

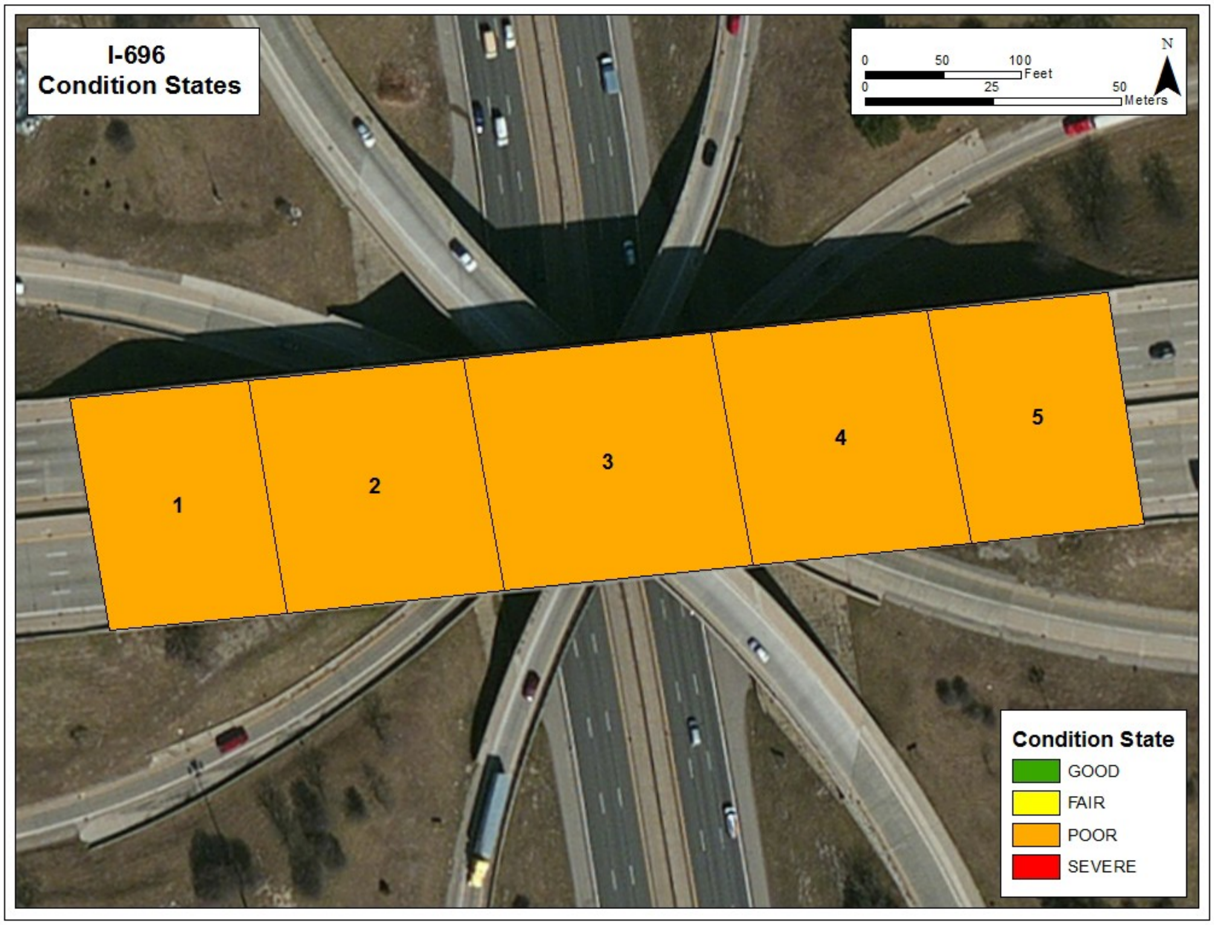


**Figure 45: Summary of condition state per deck span at I-696.**

In the 3DOBS accuracy assessment, the Lake Nepessing Rd. bridge deck contained 75 spalls manually measured within the defined two spans of the bridge deck (2 main spans and 0 approach spans). The detection of delaminations through the use of thermal imagery was not conducted on this bridge and therefore the condition state values do not contain any delamination measurements. Based on MDOT bridge inspection reports, the total bridge deck area is 11,721 ft$^2$. The total area of Condition State 2 – Fair distress features was determined to be 1 ft$^2$, or approximately 0.01% of the total bridge deck. Likewise, the total area of Condition State 3 – Poor distress features was determined to be 36ft$^2$, or approximately 0.31% of the total bridge deck (consisting of only spalls that are greater than 6 inches in diameter). The remainder of the bridge deck that did not contain any spalls was classified as Condition State 1 – Good and equated to 11,684 ft$^2$, or approximately 99.68% (Table 14 and Figure 46).

**Table 14: Condition states of each deck span for the Lake Nepessing Rd. bridge.**

| Location: Lake Nepessing | Area of Span (ft$^2$) | Area Cond. State 1 (ft$^2$) GOOD | Area Cond. State 2 (ft$^2$) FAIR | Area Cond. State (ft$^2$) POOR | Area Cond. State 4 (ft$^2$) SEVERE |
|---|---|---|---|---|---|
| Span 1 | 5924 | 5905 | 1 | 18 | 0 |
| Span 2 | 5797 | 5779 | 0 | 18 | 0 |
| **Total** | **11,721** | **11,684** | **1** | **36** | **0** |
| | | **(99.68%)** | **(0.01%)** | **(0.31%)** | **(0%)** |

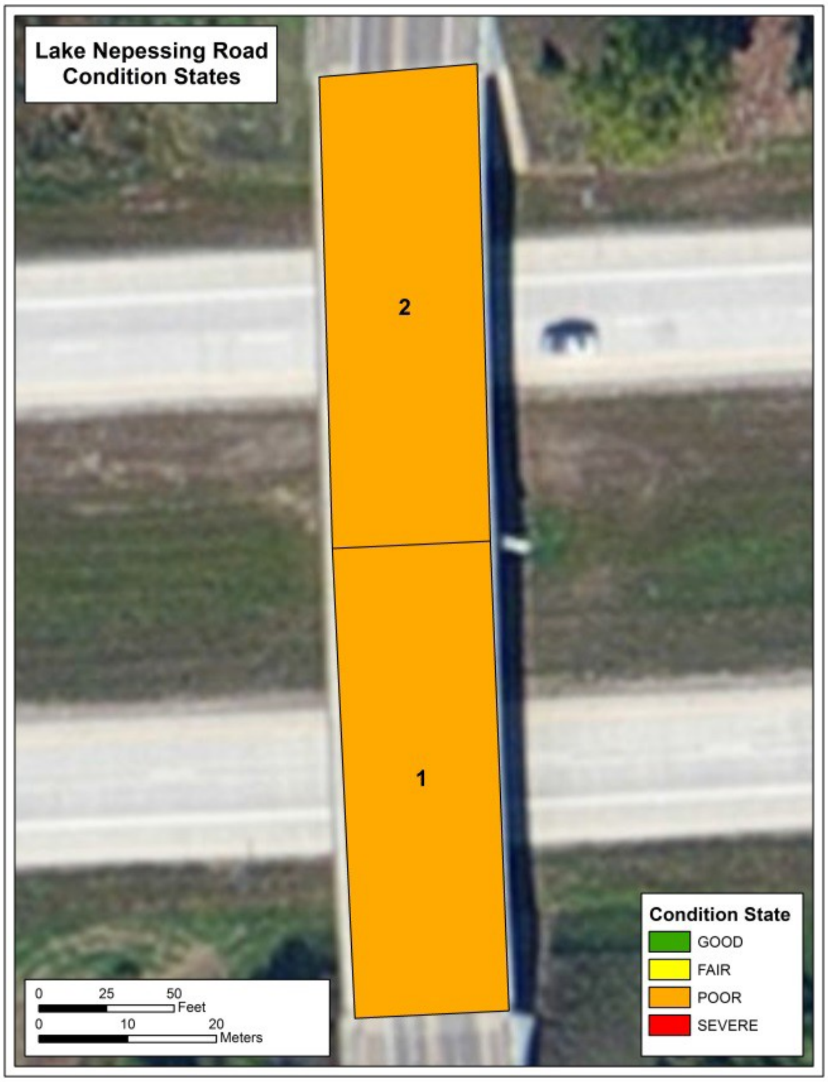


**Figure 46: Summary of condition state per deck span at Lake Nepessing Rd.**

# 5. Discussion

## *5.1 Summary of Collection and Processing Times*

### 5.1.1 Data Collection Times

The collection and processing times were recorded for each of the six large deck bridges and the accuracy assessment bridge. All of the six large deck bridges were collected over the span of four days in the field. Processing of data began shortly after completing fieldwork and is reported as a combination of person hours and computational time. The data collection of 8 Mile in Southfield, MI was completed on the first day. The next two days were devoted to travel and data collection at the two US-131 bridge decks in Grand Rapids, MI. Optical and thermal data were collected for I-75 north and southbound decks in Southgate, MI and I-696 in Hazel Park, MI on the fourth day of data collections. Because the bridges were a half hour drive from each other, data was collected for I-75 in the morning and I-696 in the afternoon. The collection started at 10:30 am on the right lane of I-75 northbound and finished on the left lane of I-696 westbound at 3:30 pm.

The amount of time needed to perform data collection per pilot study bridge is shown in Table 15. A single pass is a single collection between the beginning and end bridge joints. During the data collection on the bridges, two passes were made per lane, one on the right side of the lane and one on the left. The total collection time includes the amount of time to complete all passes, including turning around, for the whole bridge deck. For all bridge decks except for US-131, the collection started with the right side of the right lane of the north or westbound lanes. The next pass collected data from the right side of the right lane of the south or eastbound lanes. The data collection of US-131, unlike the other bridges, took two days in the field to complete. This was due to an accident in the northbound lanes, which occurred after only completing the right lane, and resulted in a backup on the northbound lanes that persisted through the prime collection hours of 9am to 4pm needed for passive thermography. The remainder of the northbound lanes data was collected the following morning. The "Average Pass per Lane" column represents the average amount of time needed to collect one lane of data with one pass over the bridge deck.

**Table 15: Data collection time by bridge.**

| Bridge | Number of Lanes | Bridge Length (ft) | Deck Area (ft$^2$) | Average Time per Pass (sec) | Total Collection Time (hr) | Comments |
|---|---|---|---|---|---|---|
| M-102 (8 Mile) | 6 | 1,838.40 | 167,662 | 34 | 0.7 | |
| US-131 North | 4 | 1,605.64 | 115,924 | 25 | 3.4 | Total for US-131 *Delay due to traffic accident on bridge* |
| US-131 South | 4 | 1,358.60 | 98,091 | 23 | | |
| I-75 North | 3 | 1,938.32 | 95,013 | 31 | 1.3 | Total for I-75 |
| I-75 South | 3 | 1,992.49 | 97,401 | 32 | | |
| I-696 | 8 | 670.00 | 102,207 | 14 | 1.6 | |

### 5.1.2 3DOBS Data Processing Time

RED Epic imagery was processed in three steps: frame extraction, geotagging, and 3D model processing. Frame extraction and model making were done through commercially available software while the frame geotagging was done through automated scripts, which were developed within MTRI. Frame extraction from the RED Epic video was completed using Adobe Premiere and involved locating the starting and ending locations of the bridge deck followed by automated frame extraction. Table 16 shows the breakdown of frame extraction times for each bridge.

**Table 16: Frame extractions times by bridge.**

| Bridge | Average Extract per Pass (min) | Average Number of Frames | Average Size per Pass (GB) | Total Extract Time Frames (hr) | Total Frames | Total Size (GB) |
|---|---|---|---|---|---|---|
| M-102 (8 Mile) | 49.8 | 1,997 | 10.4 | 10.0 | 23,964 | 124.7 |
| US-131 North | 29.1 | 1,471 | 7.46 | 4.9 | 14,719 | 74.6 |
| US-131 South | 22.4 | 1,118 | 5.9 | 2.6 | 7,828 | 41.55 |
| I-75 North | 34.8 | 1,554 | 8.32 | 3.5 | 9,327 | 49.9 |
| I-75 South | 93.2 | 1,683 | 9 | 3.9 | 10,098 | 54.07 |
| I-696 | 17.7 | 776 | 4.4 | 4.7 | 12,418 | 70.04 |

The geotagging scripts greatly improved the efficiency of completing this step. While it took roughly five hours to write the scripts and test, the scripts saved a considerable amount of time during the processing. For each of the six large deck bridges, except I-696, geotagging took just over one half an hour to complete for each lane. I-696 has a shorter bridge deck and, therefore, a shorter processing time of 14 minutes per lane. Table 17 shows the breakdown of the amount of time needed to geotag the frames from the RED Epic. Geotagging times for both US-131 bridges were not processed as the project team did not record this dataset. Based on the results from I-696 and 8 Mile, which had similar deck conditions, geotagging would not have resulted in accurate reconstruction of the bridge deck.

**Table 17: RED Epic frame geotagging times by bridge.**

| Bridge | Separating GPS by Run (min) | GPS Interpolation (min) | Locating Starting Frames and GPS Point (min) | Geotagging Frames (min) | Total Geotagging Time (hr) |
|---|---|---|---|---|---|
| M-102 (8 Mile) | 60 | 36 | 180 | 123 | 6.7 |
| I-75 North | 30 | 18 | 25 | 35 | 1.8 |
| I-75 South | 30 | 18 | 25 | 53 | 2.1 |
| I-696 | 80 | 48 | 65 | 67 | 4.3 |

After extraction and geotagging, the frames were mosaicked and georeferenced. Table 18 shows the breakdown in time for creating a mosaic for each bridge. Most of the processing time is computer-processing time. For the Photoshop correction, two hours are needed per bridge for a technician to determine the parameters for the camera orientation since camera orientation (yaw, pitch, and roll) are not recorded in the video. Manual estimations must be processed and verified on a sample set of imagery. Once obtained, parameters are entered into Adobe Photoshop and the frames are automatically corrected. This is required so that extracted frames line up and are correctly orientated to make a more accurate mosaic. The next step is represented in the "Frame Mosaic" column. This is also an automated process through scripts developed at MTRI, which mosaic all of the frames from each pass.

**Table 18: Time needed to create an optical mosaic by bridge.**

| Bridge | Photoshop Correction (hr) | Frame Mosaic (hr) | Georeferencing (hr) | Total Time (hr) |
|---|---|---|---|---|
| M-102 (8 Mile) | 32 | 3 | 12 | 47 |
| US-131 North | 24 | 1 | 8 | 33 |
| US-131 South | 24 | 1 | 8 | 33 |
| I-75 North | 16 | 2 | 9 | 27 |
| I-75 South | 16 | 2 | 9 | 27 |
| I-696 | 18 | 1 | 8 | 27 |

Table 19 shows the breakdown in processing times for the Lake Nepessing Rd bridge deck. The "GPS Interpolation" and "Correcting Orientation" columns represent analyst- processing time while the other columns represent computer-processing times. The northbound Lake Nepessing lane data took longer to correct the orientation than southbound as it was the first full model to be processed using the orientation input, and resulted in a significant amount of trial and error. Once it was determined how changing the roll, pitch, and yaw values impacted the final model orientation, the amount of time needed for this step was reduced. For future data collections, the use of an Inertial Measurement Unit (IMU) could be integrated into 3DOBS. An IMU would collect roll, pitch, and yaw values as the camera is collecting data and would eliminate the need for a technician to manually estimate and correct the orientation parameters for Agisoft processing.

**Table 19: RED Epic processing time for Lake Nepessing Rd. bridge deck.**

| Bridge Direction | Frames | Frame Extract (min) | GPS Interpolation (min) | Frame Geotag (min) | Correcting Orientation (hr) | Agisoft Processing (hr) | Total Time (hr) |
|---|---|---|---|---|---|---|---|
| Lake Nepessing North | 409 | 50 | 15 | 10 | 8 | 2.2 | 11.5 |
| Lake Nepessing South | 440 | 37 | 15 | 10 | 2 | 3 | 6.0 |

Table 20 displays the total amount of time required to process 3DOBS data and is separated between personnel and computer processing times.

**Table 20: Time required to process 3DOBS data for all study bridges split between personnel and computational time**

| Bridge | Deck Area ($ft^2$) | Total Collection Time (hr) | Extract Frames (min) | Frame Geotagging (hr) | Mosaic & Georeferencing (hr) | Orientation Correction (hr) | Agisoft Process (hr) | 3DOBS Total Time (hr) |
|---|---|---|---|---|---|---|---|---|
| **Personnel Time** | | | | | | | | |
| M-102 (8 Mile) | 167,662 | 0.7 | 1 | 4 | 15 | - | - | 19.7 |
| US-131 North | 115,924 | 1.7 | 0.67 | - | 9 | - | - | 10.7 |
| US-131 South | 98,091 | 1.7 | 0.67 | - | 9 | - | - | 10.7 |
| I-75 North | 95,013 | 0.65 | 0.5 | 0.9 | 11 | - | - | 12.6 |
| I-75 South | 97,401 | 0.65 | 0.5 | 0.9 | 11 | - | - | 12.6 |
| I-696 | 102,207 | 1.6 | 1.3 | 2.4 | 9 | - | - | 13.0 |
| Lake Nepessing | 11,721 | 0.3 | 20 | 0.5 | - | 10 | 0.2 | 31.0 |
| **Computing Time** | | | | | | | | |
| M-102 (8 Mile) | 167,662 | | 9 | 2.7 | 32 | - | - | 43.7 |
| US-131 North | 115,924 | | 4.2 | - | 24 | - | - | 28.2 |
| US-131 South | 98,091 | | 1.9 | - | 24 | - | - | 25.9 |
| I-75 North | 95,013 | | 3 | 0.9 | 16 | - | - | 19.9 |
| I-75 South | 97,401 | | 3.4 | 1.2 | 16 | - | - | 20.6 |
| I-696 | 102,207 | | 3.4 | 1.9 | 18 | - | - | 23.3 |
| Lake Nepessing | 11,721 | | 1.1 | 0.3 | - | - | 5.2 | 6.6 |

### 5.1.3 BVRCS Processing Time

To process the BVRCS data, the initial M-102 (8 Mile) processing attempts were unsuccessful due to the GoPro Hero 3 camera settings, which were set to the incorrect date and time. Therefore, instead of only having to specify the difference in time settings between the GoPro Hero 3 cameras and Trimble GPS unit, the difference in time setting between the GoPro Hero 3 cameras and actual date and time also had to be taken into account. This was different compared to previous MDOT projects where BVRCS was used for data collection and analysis. The error significantly slowed down processing times as the correct difference in date and time between the GoPro Hero 3 cameras and GPS Trimble unit had to be determined. Once the time difference was determined, processing time was significantly lowered. This time difference also had to be calculated for the other three bridge locations. However, because the process to determine the difference was already figured out, the overall processing time was lower as compared to the M-102 (8 Mile) bridge. These times are reflected in Table 21, along with the expected time it would take if these methods were implemented into MDOT inspection procedures.

**Table 21: Processing time for BVRCS**

| Bridge Location | Average Data Processing Time per Lane | Expected Data Processing Time per Lane if Implemented |
|---|---|---|
| M-102 (8 Mile) | 90 minutes | 25 – 30 minutes |
| US-131 | 45 minutes | 25 – 30 minutes |
| I-75 | 60 minutes | 25 – 30 minutes |
| I-696 | 35 minutes | 25 – 30 minutes |

### 5.1.4 Thermal Infrared Image Processing Time

Data processing for the passive thermography component of this pilot project was conducted by GS Infrastructure. Infrared Thermography images were processed in proprietary software developed by GS Infrastructure personnel. The images are manually inspected by certified ASNT-1 – Level 1 (with Level III oversight) and set-up in three steps: (1) correct configuration and overlap of the bridge elements; (2) inspection and tagging of defects in images; (3) and a separate quality review of the images. The images that are tagged as defects are then put into a client chosen CAD file and a report that is populated with automated scripts developed by the GS Infrastructure personnel. Table 22 shows the breakdown of frame extraction times for each bridge.

**Table 22: Thermal IR image review times by bridge**

| Bridge | Configure images for review | Inspection and tagging of defects | Quality Review of Images | Average # of raw images for each lane | Average # of analyzed images for each lane |
|---|---|---|---|---|---|
| M-102 (8 Mile) | 2 hr | 18 hr | 7 hr | 250+ | 100+ |
| US-131 North | 1 hr | 15 hr | 5 hr | 250+ | 100+ |
| US-131 South | 1 hr | 12.5 hr | 6 hr | 250+ | 100+ |
| I-75 North | 1.5 hr | 17 hr | 5 hr | 250+ | 100+ |
| I-75 South | 1.5 hr | 16 hr | 5 hr | 250+ | 100+ |
| I-696 | 2 hr | 18 hr | 5 hr | 250+ | 100+ |
| *Average of six decks* | *1.5 hr* | *16.1 hr* | *5.5 hr* | | |

### 5.1.5 Total Time Summary for Pilot Study Bridges

The total time documented to process, analyze, review and report the data associated with each bridge deck studied is summarized in Table 23 based on information found in Tables 15-19. The table is separated between the amount of time required for personnel hours and computer processing hours. Additionally, once the collection time was combined with the time associated to process data from each technology, the total time was divided by the total area of each bridge deck, providing the total time to process and analyze data per square foot of bridge deck. It is important to note that the total time is indicative of the processing time needed to create the optical and thermal mosaic overlays for the six large deck bridges, and does not include processing time needed to create a DEM. Because the project team was unable to process the collected 3DOBS imagery through Agisoft PhotoScan, a DEM was not produced and the imagery was mosaicked instead. Only the 3DOBS imagery collected from the Lake Nepessing bridge was fully processed through Agisoft PhotoScan which generates a DEM along with the orthomosaic layer.

**Table 23: Total processing time for each bridge.**

| Bridge Location | Area of Deck (ft²) | Collection Time (hr) | 3DOBS (hr) | BVRCS (hr) | Thermal (hr) | Total Time (hr) | Total time per ft² (sec/ft²) |
|---|---|---|---|---|---|---|---|
| **Personnel** | | | | | | | |
| M-102 (8 Mile) | 167,662 | 0.70 | 19.7 | 1.30 | 27.0 | 48.7 | 1.05 |
| US-131 North | 115,924 | 1.70 | 9.7* | 0.55 | 21.0 | 33.0 | 1.02 |
| US-131 South | 98,091 | 1.70 | 9.7* | 0.55 | 19.5 | 31.5 | 1.15 |
| I-75 North | 95,013 | 0.65 | 12.4 | 0.80 | 23.5 | 37.4 | 1.42 |
| I-75 South | 97,401 | 0.65 | 12.4 | 0.80 | 22.5 | 36.4 | 1.34 |
| I-696 | 102,207 | 1.60 | 12.7 | 0.30 | 25.0 | 39.6 | 1.39 |
| *Average of six decks* | *112,716* | *1.20* | *12.7* | *0.72* | *23.1* | *37.8* | *1.23* |
| Lake Nepessing | 11,721 | 0.3*** | 20.5 | - | - | 20.8 | 6.39 |
| **Computer** | | | | | | | |
| M-102 (8 Mile) | 167,662 | | 43.7 | 0.20 | ** | 43.9 | 0.94 |
| US-131 North | 115,924 | | 28.2 | 0.20 | | 28.4 | 0.88 |
| US-131 South | 98,091 | | 25.9 | 0.20 | | 26.1 | 0.96 |
| I-75 North | 95,013 | | 19.9 | 0.20 | | 20.1 | 0.76 |
| I-75 South | 97,401 | | 20.6 | 0.20 | | 20.8 | 0.77 |
| I-696 | 102,207 | | 23.3 | 0.20 | | 23.5 | 0.83 |
| *Average of six decks* | *112,716* | | *26.9* | *0.20* | | *27.1* | *0.86* |
| Lake Nepessing | 11,721 | | 6.6 | - | - | 6.6 | 2.03 |

* Geotagging times for both US-131 bridges were not recorded (see Section 5.1.2)

** Thermal IR used limited computer processing time.

*** Time required when the bridge is closed to traffic and 3DOBS is running at 5 mph

## *5.2 Estimating Collection and Processing Times for Future Large-deck Bridges*

A representative scenario was evaluated considering a large deck bridge with six lanes and a deck length of 1,500 ft, for a total of 108,000 sf. The summary of manual labor in hours per technology and associated costs to conduct a condition assessment of the top surface of the large deck bridge are listed in Table 24. The data collection time is based on two passes per lane due to light spalling and patching similar to I-75, and includes the time needed for each pass followed by five minutes for each turn around to begin collecting data in the opposing lanes. The estimated time for data collection of all three technologies is assumed to take place simultaneously. Estimates (time and costs) related to each individual technology studied are discussed below. A charge rate of $60 per person per hour was used to estimate the total cost of personnel hours per bridge. The table illustrates for MDOT to conduct this type of condition assessment of large deck bridges, total costs are approximately $3,100 per large deck bridge (~108,000 sf) including equipment setup, data collection, processing, analysis, quality assurance and reporting. Not included in this estimate is the cost of equipment, travel to and from the site, computing time costs, and other associated consultant fees.

**Table 24: Estimated personnel hours and cost per future large deck bridge condition assessment.**

| Task | BVRCS Time (hr) | Thermal IR Time (hr) | 3DOBS Time (hr) | Total Time (hr) | Cost (at $60/hr) | Comments |
|---|---|---|---|---|---|---|
| Equipment Setup | 0.25 | 0.25 | 0.25 | *0.75 x 2* | $90 | Two inspectors |
| Data Collection | - | - | 1.00 | *1.00 x 2* | $120 | Two inspectors, simultaneous data collection |
| Data Processing | 0.50 (0.20)* | 1.50 (**) | 3.55 (94.7)* | *5.55* | $334 | |
| Data Analysis | 3.0 | 16.1 | 8.0 | *27.1* | $1,626 | |
| Quality Assurance | 1.0 | 5.5 | 4.0 | *10.5* | $630 | |
| Reporting Results | 1.0 | 2.0 | 2.0 | *5.0* | $300 | |
| **Total** | 5.75 | 25.25 | 20.25 | *51.65* | **$3,100** | |

* value in parentheses indicates computing time (in hours) and is not included in total costs.

** Thermal IR used limited computer processing time.

Each technology was evaluated in Table 24 for personnel hours and computing hours. BVRCS analysis, quality assurance, and reporting results times are similar to the times experienced during these tasks for the six bridge decks studied in this project. BVRCS data processing time from Table 21 is included. Given that the six large deck bridges studied averaged 113,000 sf and the estimated future deck size is 108,000 sf, hours in Table 24 related to Thermal IR are averages for the six decks in Table 22 plus time for set-up and reporting.

Considering the estimates related to the 3DOBS technology in Table 24, the Agisoft processing time is estimated from the data processing method used on Lake Nepessing Rd and is expected to take the analyst less set up time to process 3DOBS data because most of the estimated processing time is computer time. Agisoft processing was completed on a desktop computer with two Intel Xenon 8-core processors, 128 GB of RAM and a NVIDIA Quadro K4000 video card with 2 GB of memory. Table 25 shows the breakdown of the total time needed to process full models of each direction of travel. The total time needed for an analyst is about 3.55 hours which includes setting up the data processing to run as well as separating the GPS by pass data, locating the starting frames and GPS points, and correcting the orientation. This estimated time is down from 12.7 hours averaged for the 6 pilot study bridge. The total amount of time needed for computer processing is 94.7 hours, up from the average of 26.9 hours reported in Table 23. It is therefore estimated that the total processing time for one analyst on a single computer to complete a DEM and orthoimage of each travel direction is approximately five days. However, the project team anticipates that significantly less time would be needed using cloud-based processing, the direction commercial close-range photogrammetry software is heading for more rapid production of processed results.

**Table 25: Estimated time to process 3DOBS data from a future bridge data collection.**

| Extract per Pass (min) | Total Extract Time Frames (hr) | Separating GPS by Run (min) | GPS Interpolation (min) | Location Starting Frames and GPS Point (min) | Frame Geotag (min) | Correcting Orientation (hr) | Agisoft Processing (hr) | Total Processing Time (hr) |
|---|---|---|---|---|---|---|---|---|
| 27 ( C) | 5.4 ( C) | 45 (P) | 12 ( C) | 24 (P) | 66 ( C) | 2 (P) | 88.4 (C/P) | 98.25 |

(P) = personnel hours; ( C) = computing hours

Also for the 3DOBS technology, almost two full days are needed to generate the full DEM and orthoimage of each travel direction of the bridge using the MTRI computers. Most of the Agisoft processing time is devoted towards the point cloud densification. In this step, Agisoft takes the sparse point cloud model and calculates additional model points based on the image alignment. There are several settings as to how "dense" the point cloud is to be generated. The setting, which is used for Lake Nepessing and this example is the medium setting, which is roughly half the resolution of the input imagery. The highest setting will result in a DEM with the same resolution of the input imagery but it would take significantly longer to process. Using the current 3DOBS setup and the "medium" setting in Agisoft, the resulting DEM will have a resolution of about 1/8 in.

Table 26 shows the estimated time needed to collect the data per technology per lane and for the entire bridge. Also estimated is the file size necessary for data storage for each respective remote sensing technology. The listed times include the time needed for each pass followed by five minutes for each turn around to begin collecting on the opposing lanes.

**Table 26: Estimated future data collection time and data storage needs for a future large deck bridge.**

| System | Time by Lane (sec) | Total Collection Time (hr) | File Size by Lane (GB) | Total File Size (GB) |
|---|---|---|---|---|
| BVRCS | 25 | 1.0 | 0.30 | 3.7 |
| Thermal IR | 25 | 1.0 | 0.237 | 2.84 |
| 3DOBS | 25 | 1.0 | 2.70 | 32.4 |

### *5.3 Project Outreach - MDOT General Training Session*

MDOT traveled to MTRI in Ann Arbor, Michigan on January 21, 2016 for a demonstration and training session of the 3DOBS and BVRCS systems. Attendance included multiple MDOT personnel and the Michigan Tech / MTRI project team members (Figure 47). The meeting began with a brief PowerPoint presentation overviewing project's objectives, 3DOBS and BVRCS data collection systems, and sample raw and processed data and imagery collected from the six big bridge decks visited during the Fall 2015 field data collections. The PowerPoint presentation was purposely kept brief as to allow more time for live demonstrations of the data collection platform and technology. Appendix B includes handouts from the training session.

**Figure 47: MDOT and Michigan Tech project members in attendance at the demonstration and training session.**

After the presentation, MDOT was led to a local Ann Arbor Area Transit Authority (AAATA) "Park and Ride" center, located at intersection of Plymouth Road and US-23, less than one mile away from the MTRI office building. While at the AAATA "Park and Ride" center, MTRI set up 3DOBS and placed the BVRCS GoPro Hero3 cameras on the hood of the data collection vehicle to demonstrate the simplicity of setting up the platform, a process that took about five minutes (Figure 48). After the platform and sensors were assembled, MTRI personnel drove across the Plymouth Road bridge over US-23 (MDOT Structure ID 10873). MTRI drove across the bridge enough times to collect 3DOBS and BVRCS data for each of the bridge's four lanes (Figure 49). During the collection, MDOT personnel stood alongside of the road and observed how quickly bridge condition data was collected using these two systems. After completing the data collection, MTRI disassembled 3DOBS and BVRCS at the AAATA "Park and Ride" while also answering questions that MDOT personnel had after observing the live data collection demonstration.

**Figure 48: MTRI setting up 3DOBS and BVRCS at the AAATA "Park and Ride".**

**Figure 49: 3DOBS and BVRCS being driven across the Plymouth Road bridge for the data collection demonstration.**

Upon returning to MTRI's office, a live data processing demonstration was given to MDOT in MTRI's GIS laboratory. During the data processing demonstration, four computers in the GIS lab were set up to demonstrate various data processing techniques and outputs associated with 3DOBS and BVRCS. MDOT personnel were split into two groups, and were given a short five minute presentation at each station, including processing steps required to build a 3DOBS composite image, 3DOBS spall and delamination detection and output, GS Infrastructure thermal delamination GIS output, and BVRCS outputs (Figures 50, 51, and 52). The data used for these demonstrations were a subset of the data collected during the Fall 2015 field data collections which eliminated the processing time necessary to obtain output from data captured minutes earlier during the live demonstration. MDOT personnel were able to ask questions while watching the live data processing procedures, in which MTRI project team members were able to answer through the live data processing demonstrations. Project progress and further questions or concerns were addressed before the conclusion of the meeting.

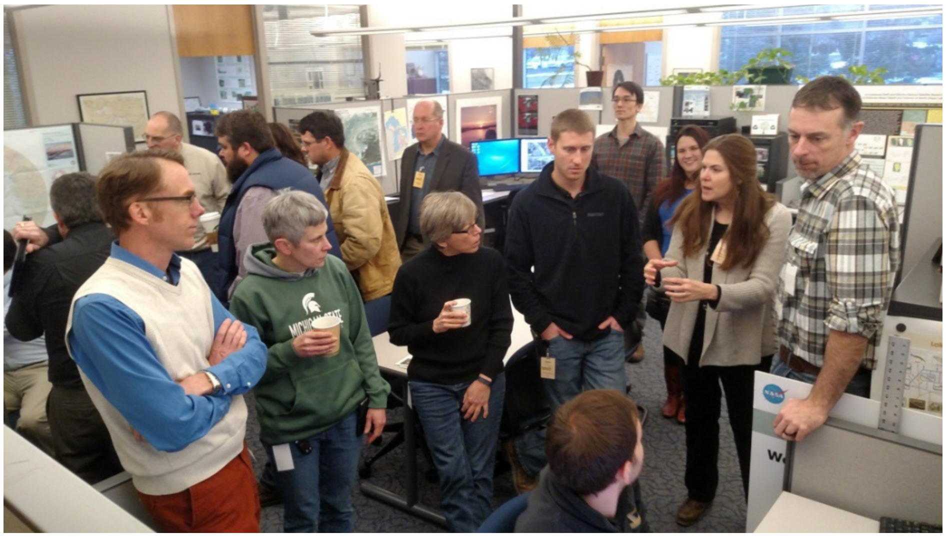

**Figure 50: Project Principle Investigator, Professor Tess Ahlborn, providing insight into data processing and outputs.**

**Figure 51: MTRI project team member, Rick Dobson, providing an overview of 3DOBS imagery processing and output.**

**Figure 52: MTRI project team member, David Banach, providing an overview of BVRCS imagery processing and output.**

# 6. Conclusions

## *6.1 Conclusions from the Study*

This research project investigated NDE technologies, specifically remote sensing technologies including photogrammetry and thermography, for deployment at near highway speeds to assess the top surface condition of large concrete bridge decks. Several non-destructive technologies validated in previous projects were combined on the same data collection vehicle including 3DOBS, passive infrared thermography, and BVRCS, as an integrated system for condition assessment of the top surface of concrete bridge decks. Integrated data sets can lead to more effective asset management decisions through a more thorough understanding of deck condition.

The 3DOBS system was previously upgraded to a near highway speed version capable of allowing the collection vehicle to travel at speeds up to 45 mph with a high-resolution camera capable of detecting spalls at this speed. The RED Epic was chosen for near highway speed data collections due to its ability to collect 13.8 MP imagery at up to 60 fps. This project successfully demonstrated that distress features such as spalls and delaminations could be detected and quantified at near-highway speeds, on large deck bridges (>95,000 sf) without the need to close traffic lanes. Due to the relatively good condition of the large bridge decks studied (i.e. minimal spalling), full reconstructions of the large-deck bridges were not possible. With enhanced Agisoft processing techniques, sections of the I-75 bridges and the entire Lake Nepessing Road bridge (both of which contained numerous spalls) could be achieved and were demonstrated near the project's end.

When 3DOBS was combined with passive infrared thermography on the same vehicle mount, both surface and subsurface conditions were assessed with a single pass per lane. Optical and thermal datasets were referenced to the same coordinates and viewed in GIS such as ArcMap. The creation and use of separate GIS data layers generated from the collected imagery was successfully demonstrated, including an orthoimage, digital elevation model DEM, Hillshade of the DEM, thermal mosaic, detected spalls layer, and potential delaminations layers. A combination of these layers would enable MDOT to perform change detection analysis on the distresses and provide objective data to generate NBI ratings for the bridge deck (based on deck surface element defect quantification and location information collected).

BVRCS has again proven to be a low cost, valuable tool for collecting a high-resolution photo inventory of bridges providing information to inspectors and agencies. The GeoJot+ software allows for the creation of shapefiles consisting of interpolated points corresponding to the location each photo was captured. Each point was linked to a watermarked version of the collected photo that can be displayed in ArcMap or Google Earth.

Separately, the three technologies demonstrated in this pilot project provide MDOT with a more detailed understanding of bridge deck condition. When combined, these three technologies would ensure MDOT could conduct bridge deck inspections while keeping inspectors safe and are unexposed to traffic (i.e. walking along traffic shoulders), as well as eliminating the need to close down lanes and passing the time savings onto the traveling public.

The total time needed to complete the processing of the large deck bridges during this study was reported in Table 23, and averaged 37.6 personnel hours and 27.1 computing hours. From this analysis, the average amount of personnel time needed to complete a large deck bridge was 1.23 sec/ft$^2$. Cloud-based processing should significantly shorten this processing time in the future. Future data collections on bridges with spalling similar to the I-75 bridges can be processed through Agisoft PhotoScan to generate an orthoimage and DEM, reducing personnel time while increasing computing time. This supplies the end user with spall depth information and most of the 3DOBS processing time is computer time as opposed to the mostly manual methods used to derive final products for the six large deck bridges.

Considering a representative large deck bridge of 108,000 sf and a condition similar to that of the I-75 bridge decks, an estimate of personnel hours, associated costs, and computing time was determined to be \$3100 per large deck bridge (Table 24). The estimate includes equipment setup, data collection, data processing, data analysis, quality assurance review and reporting of results for the three remote sensing technologies considered. The estimate does not include the cost of equipment, travel to and from the site, computing time costs, and other associated consultant fees.

The condition state tables in Section 4.3.6 show the ability to not only identify, spatially locate, and quantify distress features such as spalls and delamination along the bridge deck, but also the ability to separate these features by span and assign condition ratings. By using the Michigan Bridge Element Inspection Manual, which defines the quantitative measurements of distress features by condition state, the analysis was able to indicate the condition state of distress features and spans for the six bridges. Each of the six bridges only had spans that were overall within the "fair" and "poor" states due to the fact that each span had some type of distress feature. "Severe" span condition states were not identified during this analysis due to the lack of severe distress feature damage to any of the bridge decks. Overall, the ability to define the condition state of both the distress features and spans provided visualizations that could potentially help a bridge inspector quickly determine the condition of distress features and spans along a bridge deck. Additionally, through periodic inspections of the bridge deck, the condition states could quickly be updated in the GIS (in which these visualizations are based) to reflect the current condition of the bridge deck.

A general training session was held to provide MDOT inspectors and end users the tools and knowledge to use the presented non-destructive remote sensing technologies for effective asset management. Hands-on equipment demonstrations allowed attendees to have one-on-one discussions with researchers on the use, costs, and benefits of the technologies. Additionally, a live demonstration of data collection procedures was conducted on a sample bridge, allowing MDOT personnel to experience firsthand how quick data collection occurs. The training session confirmed that bridge inspectors are interested in using advanced technologies for routine, detailed and scoping inspections.

## *6.2 Recommendations for Further Research*

Combining remote sensing technologies to assess the condition of a concrete bridge deck has been shown to be very useful to enhance bridge inspection. As the performance of cameras continues to advance, additional health indicators or condition state will be detectable. It is strongly recommended that MDOT keep abreast of changes in technology through additional interactions with the project team, especially as faster, less expensive camera models are released and secure cloud-based imagery processing becomes more practical.

The use of unmanned aerial vehicles (UAVs) for condition assessment has a growing popularity. Remote sensing technologies, including optical, thermal, and LiDAR, have been successfully demonstrated to MDOT through other research opportunities ("Evaluating the Use of Unmanned Aerial Vehicles for Transportation Purposes", 2013-067, No. 1, OR13-008, led by PI C. Brooks). Combining UAVs with the data fusion and common platform for technologies can enhance inspection for bridge decks, superstructures, and other transportation infrastructure. Pilot studies are recommended to demonstrate the optimal use of UAVs for condition assessment of bridge decks, in relation to vehicle-based and manual assessment, building from MDOT's recent research investment in this area. During this project's period of performance, the Michigan Tech Research Institute successfully applied and was selected for Phase II of the "Evaluating the Use of Unmanned Aerial Vehicles for Transportation Purposes" research project. Conclusions and lessons gained from this research project will likely be applied to the Phase II project.

As experts in remote sensing applications for transportation infrastructure, the project team is available to assist MDOT with their future research needs in an area of rapidly changing technology. Data processing techniques for assessment of a variety of health indicators are yet to be developed and can be applied to a host of situations including evaluation of steel and timber superstructures and substructures. Future research could address these additional bridge types and construction materials.

## *6.3 Recommendations for Implementation*

An Implementation and Action Plan (IAP) is based on the IAP developed for the first funded phase of this project, with updates based on an extended phase focused on deploying the integrated vehicle-based sensing tools over six large bridges and detailed accuracy evaluation of 3DOBS. This updated IAP is meant to direct the RAP and other interested MDOT personnel in applying changes within the department's policies and/or practices. Recommendations on how MDOT can incorporate vehicle-based NDE remote sensing technologies for bridge condition assessment are also provided. The plan is included in Appendix D.

BVRCS, a system shown to provide high resolution imagery using GoPro cameras to discern spalls and patchwork on a concrete deck while traveling at 45 mph and above, is near ready for deployment. The system is commercially available and low cost (less than $1000), and can provide an assessment method comparable to visual inspection in a very short time. The system was demonstrated during the demonstration session held at the MTRI in Ann Arbor. It is recommended that MDOT begin with introducing the system into one region for all upcoming inspections. Inspectors will quickly learn the system operation and gain the benefit of having a high-resolution geotagged photo inventory of the bridge deck collected while travelling at highway speed without traffic interruption.

Top of deck evaluation at near highway speed can also include the detection of spalls, cracking, and suspected delaminations by combining 3-D photogrammetry and thermography data collections. By demonstrating and deploying the combined systems at near highways speeds for six large bridges, MDOT now has access to a system that can collect optical and thermal data for assessing the location and size of spalls and potential delaminations at speeds of 45 mph. The 3DOBS technology used for spall detection did encounter a technological challenge where bridge decks in good or excellent condition (with few or no spalls) did not have sufficient surface height diversity to create a 3D model of the entire large bridge decks. However, a mosaicked, georeferenced image map of the bridge could be created, the thermal data could be referenced to it, and a GIS layer of potential delaminations from GS Infrastructure's thermal system could be overlaid on these data. A data processing breakthrough was reached late in the project so that bridge decks that did have significant spall defects could be processed into a 3D data set for automated spall detection. As part of this breakthrough, full 3DOBS assessment (using Agisoft to process 3D models of the bridge deck) should be used for bridge decks with known spalling distresses, which would allow for 3D model reconstruction. For bridges with minimal or no spalling, mosaicking the collected 3DOBS imagery has been shown to be effective in creating base maps for other datasets and manual inspection of the deck surface. It is recommended that these remote sensing technologies be integrated to the bridge inspector's suite of tools for inspection. Capital investment in equipment, training of inspectors, and coordination with the MDOT Design Survey office are necessary for implementation.

Common to the implementation of all these technologies, is the tough question that MDOT must assess thoroughly to fully understand the path to implementation. How will these data be used? Based on this project's results, the project team strongly believes that MDOT can now collect bridge deck condition data without need to close traffic lanes, extended phase findings to understanding if processing time and lack of complete 3D data set for good bridges still meet the agency's condition assessment needs, and use BVRCS to retrieve StreetView-style imagery whenever needed for bridges. MDOT can decide on collecting these data in house, and on making these combined methods an option for their contracted third-party inspection services for spall and delamination data. The value added to MDOT now includes an understanding of the limits of 3D optical technology for large bridge decks, especially those in good condition with few spalls, and big bridges (or essentially any bridge) do not require traffic closures for the collection of data. Traffic escort vehicles may still be a good idea as traveling at near-highway speeds (i.e. 45mph) still disrupts traffic flow patterns. Lastly, MDOT now has access to a professional grade, high resolution, high frame rate camera it can deploy and/or further evaluate, along with other technologies it can implement in daily bridge deck evaluation.

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# Appendices

## *Appendix A: List of Acronyms, Abbreviations, and Symbols*

3DOBS – 3-D Optical Bridge-evaluation System

AAATA – Ann Arbor Area Transit Authority

BVRCS – Bridge Viewer Remote Camera System

DEM – Digital Elevation Model

EXIF – Exchangeable Image File format

FLIR – Forward Looking Infrared Radiometer

FPS – Frames per Second

FOV – Field of View

GIS – Geographic Information System

GPS – Global Positioning System

IAP – Implementation Action Plan

IMU – Inertial Measurement Unit

MP – Megapixel

MTRI – Michigan Tech Research Institute

NBI – National Bridge Inventory

NDE – Non-Destructive Evaluation

RAP – Research Advisory Panel

SSD – Solid State Hard Drives

UAV – Unmanned Aerial Vehicles

## *Appendix B: Training Session Handouts*

3-D Optical Bridge Evaluation System (3DOBS) and
Bridge Viewer Remote Camera System (BVRCS)
Live Demonstration and Training Session

Michigan Tech Research Institute (MTRI), 3600 Green Ct., Ste. 100, Ann Arbor, Michigan
Lake Superior Conference Room
Thursday, January 21, 2016; 9am – 11am

9:00am – 9:30am: Introductions and Overview of 3DOBS and BVRCS Equipment (at MTRI)

- Lake Superior Conference Room, MTRI

9:30am – 9:40am: Drive to Demonstration Bridge (Plymouth Road at US-23)

- For the demonstration, we will drive to the nearby Plymouth Road "Park and Ride"

9:40am – 10:00am: Live 3DOBS and BVRCS Demonstration

10:00am – 10:10am: Return to MTRI

10:10am – 10:50am: Live Data Processing and Data Output Demonstration

- MTRI GIS Laboratory

10:50am – 11:00am: Questions and Wrap-up

- Lake Superior Conference Room, MTRI

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MDOT Project #: OR10-043, Auth. No.7, R1-R4

**Evaluation of Bridge Decks using NDE at Near Highway Speeds for Effective Asset Management**

3DOBS Training Session
Thursday, January 21, 2016
Ann Arbor, MI

## Today's Outline

- Introductions
- Overview of 3DOBS and Equipment
- Data Collection Live Demonstration
- Data Output and Processing Demonstration
- Q & A

## Project Objectives

- Demonstrate the capabilities of combined thermal and optical imaging at near highway speeds for condition assessment of large deck bridges.
- Demonstrate the accuracy of 3DOBS optical imaging for assessment of spalls and cracking on bridge decks.

*Tasks*

1. Prep and Data Collection for Large Bridge Decks
2. Data Processing and Condition Assessment
3. Accuracy Assessment for 3DOBS optical imaging
4. Impacting Technology Transfer
5. Final Reporting

## 3DOBS Highway Speed Spall Detection

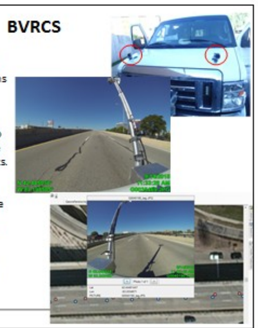
- Red-EPIC camera system
- 13.8 MP up to 60 frames per second
- $30,000 for the camera and its components


## BVRCS

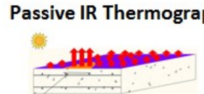
- GoPro HERO3
- 12 Megapixel photo capability
- Lightweight, camera: 74g (2.6 oz) and camera with housing: 136g 4.8 oz)
- Up to 12 frames per second at 8.8 MP
- $300 - $400

## BVRCS

- Low cost (<$1,000) deployable system that provides visual analysis of bridge deck conditions at the time of data collection.
- Consists of two GoPro Hero3 cameras that can be mounted to any vehicle and used at multiple sites without any additional costs.
- Images are processed and geotagged through GeoJot+ Core
- Hyperlinks are set up using both ArcMap and GeoJot+ Core capabilities allowing for visualization of the condition of the bridge deck at defined locations



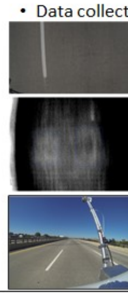
## Passive IR Thermography (GS Infrastrucutre)




- Sun provides thermal impulse
- Heat transfers from surface to concrete interior
- Delaminations restrict heat transfer and appear as hot spots on thermal images during daytime hours
- Maximum contrast occurs during specific testing time window

## 8 Mile

- Data collected on September 14, 2015



## I-75 at Goddard

- Data collected on September 17, 2015

## I-696 at I-75

- Data collected on September 17, 2015

## US-131 at Grandville – Grand Rapids

- Data collected on September 15-16, 2015

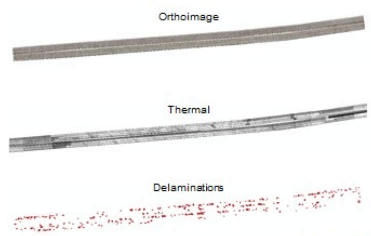
## Passive IR Thermal into GIS

- Thermal Infrared data provided by GS Infrastructure
- Using ArcGIS software, MTRI georeferenced and mosaiced these data.
- These data can now be combined with other geospatial datasets (spall detection from 3DOBS).

## NDE Technology Integration for Top of Bridge Deck

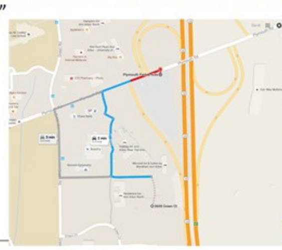
- All collected data and results are either GIS rasters or shapefiles and can be easily displayed and overlaid in a GIS.
- Data and Results Output:
  - Orthoimage
  - Thermal Image Mosaic
  - Detected Spalls Layer
  - Detected Delaminations Layer

## 8 Mile Datasets




## Data Collection Live Demonstration

- Please park at the Plymouth Road "Park and Ride"



## Data Output and Processing Demonstration

- MTRI GIS Lab
- Each station in the GIS lab will demonstrate the data processing and output for the following technologies:
  - 3DOBS Composite Image
  - 3DOBS Spall and Delamination Detection and Output
  - GS Infrastructure Thermal Delamination GIS Output
  - BVRCS

## Other Questions or Concerns?

MichiganTech
Create the Future

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## Contact Information

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Jennifer.Julien@gsinfrastructure.com

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## *Appendix C: Lake Nepessing Field Data Sheets*

| ID | Feature Type | Length | Width | Depth |
|---|---|---|---|---|
| JS-1 | spall | 6.75 | 4.75 | 1.00 |
| JS2 | spall | 2.25 | 1.25 | .75 |
| JS3 | spall | 6.5 | 4.25 | .75 |
| JS4 | patch | 32.25 | 17.5 | |
| JS5 | spall - rebar | 20.5 | 12.0 | 2.25 |
| JS6 | spall | 6.0 | 4.25 | .75 |
| JS7 | spall | 7.5 | 3.25 | .75 |
| JS8 | spall | 2.0 | 2.0 | .5 |
| JS9 | patch | 11.5 | 7.0 | |
| JS10 | spall | 6.25 | 3.25 | .5 |
| JS11 | spall | 9.5 | 6.0 | .75 |
| JS12 | spall | 8.25 | 3.0 | .5 |
| JS13 | spall | 9.25 | 8.25 | 1.0 |
| JS14 | spall | 13.5 | 29.5 | 2.25 |
| JS15 | SPALL | 7.0 | 2.75 | .75 |
| JS16 | SPALL | 27.0 | 10.0 | 2.00 |
| JS17 | SPALL | 17.0 | 3.00 | .75 |
| JS18 | SPALL | 17.0 | 7.25 | 1.25 |
| JS19 | SPALL | 10.0 | 3.75 | 1.0 |
| JS20 | PATCH | 16.0 | 6.75 | |
| | | | | |

| ID | Feature Type | Length | Width | Depth |
|---|---|---|---|---|
| JS21 | SPALL | 6.50 | 2.50 | .50 |
| JS22 | SPALL | 3.50 | 2.00 | .50 |
| JS23 | PATCH | 23.50 | 13.00 | |
| JS24 | SPALL | 14.00 | 6.00 | 1.25 |
| JS25 | SPALL | 18.50 | 10.25 | 1.50 |
| JS26 | SPALL | 13.25 | 4.00 | 1.00 |
| JS27 | SPALL | 16.00 | 5.50 | 2.25 |
| JS28 | SPALL | 11.75 | 5.25 | 1.25 |
| JS29 | SPALL | 13.50 | 7.50 | 1.75 |
| JS30 | SPALL | 16.50 | 10.50 | 1.50 |
| JS31 | SPALL | 16.25 | 4.50 | 1.50 |
| JS32 | SPALL | 12.25 | 4.50 | 1.00 |
| JS33 | SPALL | 17.00 | 6.00 | 1.50 |
| JS34 | SPALL | 13.75 | 4.00 | 2.00 |
| JS35 | SPALL | 5.00 | 2.50 | 0.50 |
| JS36 | SPALL | 6.5 | 2.25 | 1.0 |
| JS37 | Spall | 3.75 | 6.25 | 1.0 |
| JS38 | Spall | 5.5 | 3.25 | 1.25 |
| JS39 | Spall | 20.0 | 12.5 | 1.75 |
| JS40 | Spall | 13.0 | 4.5 | 1.0 |
| JS41 | Spall | 10.75 | 4.5 | 1.25 |

| ID | Feature Type | Length (cm) | Width (cm) | Depth (cm) |
|---|---|---|---|---|
| LN1 | Spall | 11.5 | 8.2 | 1.7 |
| LN2 | Spall | 16.8 | 13 | 2.9 |
| LN3 | Spall | 27.1 | 11.6 | 1.6 |
| LN4 | Spall | 11.6 | 9.4 | 2.2 |
| LN5 | Spall | 35.8 | 15.2 | 3.7 |
| LN6 | Patch | 16.6 | 12.5 | X |
| LN7 | Spall | 18.4 | 7.8 | 2.1 |
| LN8 | Spall | 17.2 | 10.7 | 2.0 |
| LN9 | Spall (w/ patch) | 18.0 | 10.0 | 1.8 |
| LN10 | Spall | 26.5 | 12.3 | 2.5 |
| LN11 | Spall | 14.0 | 11.1 | 2.2 |
| LN12 | Spall | 24.2 | 12.3 | 2.6 |
| LN13 | Spall | 21.6 | 9.7 | 1.8 |
| LN14 | Patch | 22.0 | 16.9 | X |
| NL15 | Patch | 23.5 | 7.5 | X |
| LN16 | Spall (in patch) | 34.4 | 3.4 | 1.4 |
| LN17 | Spall (in patch) | 10.2 | 10.1 | 1.0 |
| LN18 | Patch | 40.3 | 35.2 | X |
| LN19 | Spall | 11.6 | 7.6 | 1.6 |
| LN20 | Spall | 29.6 | 18.1 | 2.1 |
| LN21 | Spall | 59.5 | 33.4 | 5.8 |
| LN22 | Spall | 26.5 | 8.6 | 1.5 |

2/23/13 Lake Napising lanes C/D pal IFES/EKS

| ID | Feature Type | Length cm | Width cm | Depth cm |
|---|---|---|---|---|
| LN23 | Spall | 12.2 | 9.7 | 1.4 |
| LN24 | Spall (in spall in patch) | 38.1 | 6.9 | 2.5 |
| LN25 | Spall | 27.6 | 7.2 | 2.5 |
| LN26 | Spall | 17.3 | 6.3 | 1.8 |
| LN27 | Spall | 32.6 | 8.2 | 2.5 |
| LN28 | Spall (in patch) | 48.6 | 20.0 | 1.9 |
| LN29 | Spall | 10.2 | 6.5 | 1.1 |
| LN30 | Spall | 10.1 | 9.5 | 2.0 |
| LN31 | Spall (in patch | 17.8 | 9.5 | 1.9 |
| LN32 | Spall (in patch) | 19.2 | 5.7 | 1.3 |
| LN33 | Spall (in patch) | 15.2 | 11.2 | 1.6 |
| LN34 | Spall (in patch) | 72.6 | 30.5 | 4.5 |
| LN35 | Spall | 53.1 | 28.1 | 4.8 |
| LN36 | Spall | 19.7 | 8.5 | 2.2 |
| LN37 | Spall | 19.6 | 11.5 | 2.7 |
| LN38 | Spall in patch | 24.8 | 9.4 | 2.0 |
| LN39 | Spall | 17.0 | 10.4 | 1.8 |
| LN40 | Spall | 21.2 | 9.0 | 2.7 |
| LN41 | Spall | 67.0 | 32.8 | 4.7 |
| LN42 | Spall | 32.2 | 21.6 | 2.8 |
| | | | | |

2/23/2016 Lake N

Lanes 4/3 Pad | GESIFKS

## *Appendix D: Implementation Action Plan*

This implementation action plan (IAP) is based on the IAP developed for the first funded phase of this project, with updates based on an extended phase focused on deploying the integrated vehicle-based sensing tools over six large bridge decks and detailed accuracy evaluation of the 3DOBS technology. This updated IAP is meant to direct the Research Advisory Panel and other interested MDOT personnel in applying changes within the department's policies and/or practices. This guide provides an overview of the extended phase of the project and the problems it focused on changing. The outcomes and potential values to MDOT are reviewed. Recommendations on how MDOT can incorporate vehicle-based NDE remote sensing technologies for bridge condition assessment are also provided.

**Project Title:** *Evaluation of Bridge Decks using Non-Destructive Evaluation (NDE) at Near Highway Speeds for Effective Asset Management – Pilot Project (RC-1617B)*

**Project Number:** Contract no. 2010-0295, Auth. No. Z7, Rev. No. R4, Research no. OR10-043

**Principal Investigator:** Theresa (Tess) M. Ahlborn, Michigan Technological University

**Project Manager:** Eric Burns, MDOT

**Research Manager:** Michael Townley, MDOT

**Description of Problem**

The first phase of this project evaluated mobile (vehicle-based) optical and thermal remote sensing technologies in comparison to traditional bridge assessment techniques, such as coring, chain drag, etc. (Ahlborn and Brooks, 2015). The project demonstrated that optical and thermal sensors combined on a near highway-speed vehicle-based system could be used to collect data on spalls, potential delaminations, and cracking on a practical basis. This phase focused on deploying the combined systems (thermal Infrared and 3DOBS) at near highways speeds for six large concrete bridge decks selected by MDOT (deck area > 90,000 sf), using GS Infrastructure Inc.'s data collection van. MDOT, and their contracting condition assessment companies, now have access to a system that can collect optical and thermal data for assessing the location and size of spalls and delaminations at speeds of 45 mph. The BridgeViewer Remote Camera System (BVRCS) was also deployed to collect location-tagged bridge deck photo inventories with an inexpensive dual camera plus GPS system.

The 3DOBS technology used for spall detection was compared to field hand measurements to evaluate accuracy. A technological challenge was encountered where bridge decks in good or excellent condition (with few or no spalls) did not have sufficient surface height diversity to create a 3D model of the entire large bridge deck. However, a mosaicked, georeferenced image map of the bridge could be created, the thermal data was referenced to it, and a GIS layer of delaminations from GS Infrastructure's thermal system was overlaid on these data. A data processing breakthrough was reached late in the project so that small areas of high-quality bridge data that did have spall defects could be processed into a 3D data set for automated spall detection.

A training session showed a representative 3DOBS data collection process, including GIS lab processing methods, and received positive feedback from MDOT. Included was a depiction of spalling and delamination amounts by condition class and by bridge deck section, showing how these can be depicted graphically within a GIS.

**Major Discoveries:**

For this second (pilot project) phase (Revision No. R4), results showed that optical and thermal technologies could be deployed for large concrete bridge decks at near highway-speed, with certain technological limitations. These data can be summarized in a map-based and table-based element level summary with percentage and area by condition state and by span.

3DOBS was successful for finding spalling for small areas with defects on otherwise good bridges, but was not able to create a complete 3D surface for entire large bridge decks when used at near-highway speed with the RED Epic camera. However, the team developed an alternative mosaicked, georeferenced GIS output that served as a base map for referencing the thermal output and detected delaminations. Spalls could be manually digitized off this base map if 3D reconstruction was not possible for an area with these distresses. These data could be collected at a near highway speed of 45 mph with the RED Epic camera, with no need to close traffic. Processing time was still significant, but operational use is expected to be lower, especially as computing power continues to increase.

For passive thermography, a GIS output layer of delaminations, as suggested by the GS Infrastructure system, could be created for entire bridge deck and collected at the same time, from the same mount, as the 3D optical data. A thermal infrared combined GIS layer could be created, and these systems, set to a common coordinate system (such as Michigan Georef, or the locally appropriate State Plane system), are available for integrating into CAD software as well.

The combined data of spalls and delaminations could be summarized in condition state tables with areas and percentages, which are data needed for element-level inspection reporting. These data can be represented as either summary tables, or as map-based outputs that show condition state by spans, and/or for each detected spall or delamination.

The BVRCS tool was able to create comprehensive GPS-tagged photo inventories of the large concrete bridge decks, to serve as a "StreetView" style system that can be updated as needed by MDOT, rather than having to rely on Google updates. It is necessary to be aware of the with date/time camera settings on the BVRCS cameras (such as the GoPro units that were used) to easily match to GPS track data needed for geopositioning. A dedicated inexpensive (<$500) GPS unit can be helpful in obtaining the needed track data.

**How the Information will be used in MDOT:**

These results demonstrate that MDOT can reasonably collect bridge deck condition data without the need to close traffic lanes. Passive thermography data, 3D optical data, plus GPS-tagged and easily updated photo inventories can be created and used as part of bridge inspections. These data track changes over time as well, as future condition inventories can be overlaid on top of previous ones, which is useful for deterioration tracking and modeling. MDOT can use these pilot project findings to understand if processing time and lack of complete 3D data set for good bridge decks still meet the agency's condition assessment needs. As camera technology improves, the answer will go from an "initial" yes to a "firm" yes. For example, the newer RED Dragon camera has a 19 mp sensor capable of 100 fps, versus the older RED Epic system with 13.8 mp at 60 fps; this improves the ability to do 3D reconstructions at faster speeds, while potentially adding crack detection.

As noted in the previous phase final report, BVRCS is ready to use now, with its inexpensive hardware setup. MDOT can get readily updated StreetView-style imagery whenever needed. This can also serve as a location-tagged record of the bridge environment that can be useful to track change over time.

Based on these project results, MDOT can now decide on collecting these data in house, and on making these combined methods an option for third-party companies that provide inspection services on a contractual basis. If MDOT expects these companies will provide numeric data on amount and location of spalls and delaminations, especially as part of element-level inspections, then the combined 3DOBS plus thermal data collection methods are likely to make business sense as a service.

With these technologies, MDOT now has options other than physically sounding a bridge deck with lanes closures to determine delamination areas and spalls. MDOT could use these technologies (thermal infrared, 3DOBS, and BVRCS) to determine bridge deck condition states, defect quantities, and defect locations without adversely impacting traffic. The decision to use these technologies may be made at the MDOT region level or at the MDOT Central Office. The MDOT Region Bridge Engineer may elect to use to all or some of the technologies on a corridor project with high volume interstates routes structures with traffic control restrictions. The Region Bridge Engineer may also elect to use the technology on an "as needed" basis to supplement staffing shortages. MDOT Central Office may elect to use the technology as part of detailed scoping of a big bridge deck project or as part of a detailed scoping of interstate corridor projects as well.

**Value Added to MDOT**:

The tools, methods, and results described in this report provide several added value options that MDOT can now more easily take advantage of. First and foremost, these systems can provide high-quality data on concrete bridge deck condition at near highway speed without the need to close traffic lanes. The methods are repeatable, providing a valuable data set that can now be used to track location-specific change over time. Because the 3D optical and thermal outputs are location-specific, quantitative data, element level condition states by span can easily be calculated and visualized in tabular and map-based formats. The inexpensive BVRCS tool has a well-defined methodology with location-tagged photos that integrate well with other sources of inspection data. These data have the capability to be visualized on new 3D bridge inspections, such as the 3D BRIDGE app currently undergoing second-phase development.

Through this applied research, MDOT has improved understanding of the strengths and limitations of 3D optical technology. Large bridge decks with few spalls provide a challenge to 3D optical sensing that an active system, such as laser scanning, may not experience when creating complete 3D maps of bridge decks. However, improving fast frame rate cameras with decreasing costs may provide a solution to this issue. 3DOBS provides a georeferenced imagery set even when complete 3D imaging is not technically possible.

MDOT now has access to another way of collecting bridge deck condition data that does not require closure of the bridge. Some traffic control, in the form of an escort vehicle may still be need, if the current deployment speed of 45 mph would cause traffic problems. Newer, faster high-frame-rate cameras should push data collection speeds past 45 mph, with 60mph seeming reasonable with the newest commercially available systems.

It should be noted that as a result of this project, MDOT owns a professional grade, high resolution, high frame rate camera to deploy and/or further evaluate as needed. Transfer of the Red

EPIC camera to MDOT was completed in May of 2016. MDOT should ensure that it exploits the availability of this system to obtain maximum value out of its investment through continued usage on a regular basis.

**Implementation Plan Checklist**:

The following checklist provides a summary for MDOT on understanding the types of results achieved through this project and the items and actions necessary to implement the results. It is similar to the Phase I report, except that we are concluding this particular research program.

| Results achieved through this research (check all that apply) | | Items/Actions needed to implement results (check all that apply) | |
|---|---|---|---|
| X | Knowledge to assist MDOT | X | Management decision |
| | Manual change | X | Funding |
| | Policy development or change | X | Training |
| X | Development of software/computer application | X | Information technology deployment |
| X | Development of new process | X | Information sharing |
| | Additional research needed | | Other (specify) |
| | Project produced no usable results | | |
| | Other (describe) | | |

**References:**


Ahlborn, T.M., and C.N. Brooks, 2015 "*Evaluation of Bridge Decks Using Non-Destructive Evaluation (NDE) at Near-Highway Speeds for Effective Asset Management*," MDOT Research Report RC-1617, Michigan Department of Transportation, Lansing, MI.