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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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%)**

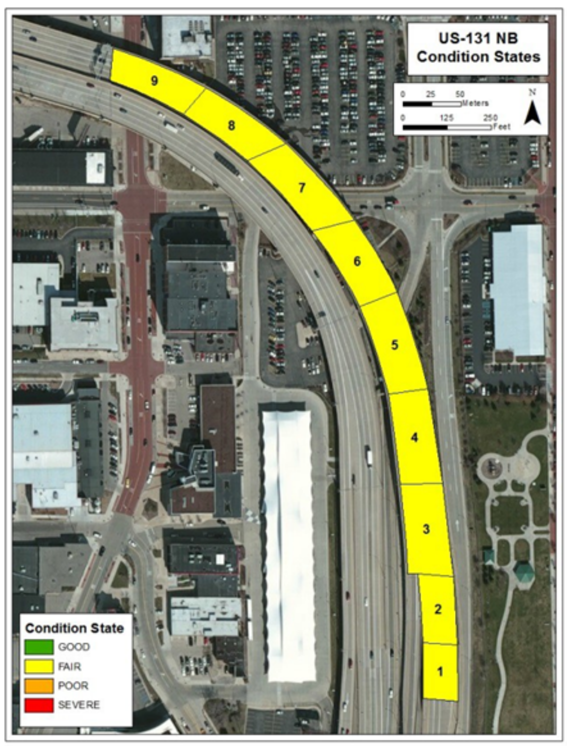

Figure 1: Summary of condition state per span at US-131 northbound.

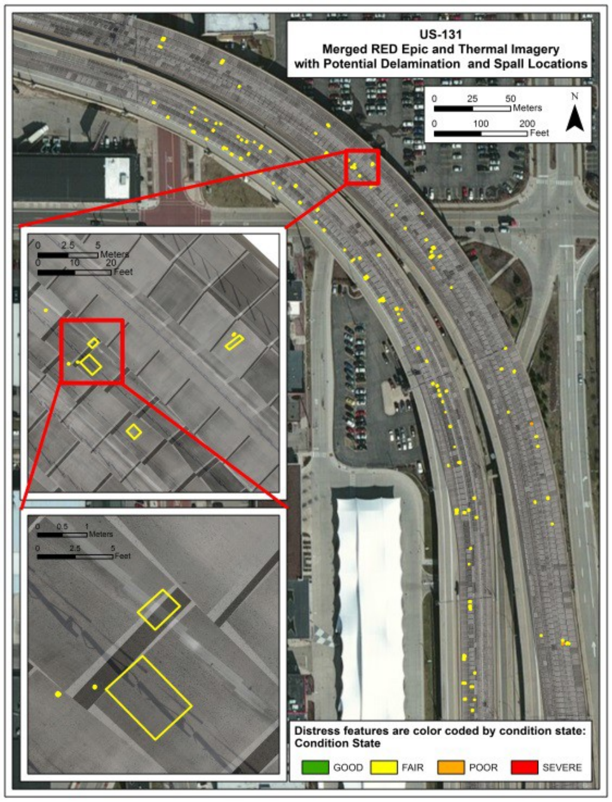

Figure 2: Location of potential delaminations and spalls on US-131 northbound and southbound bridge decks.

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).

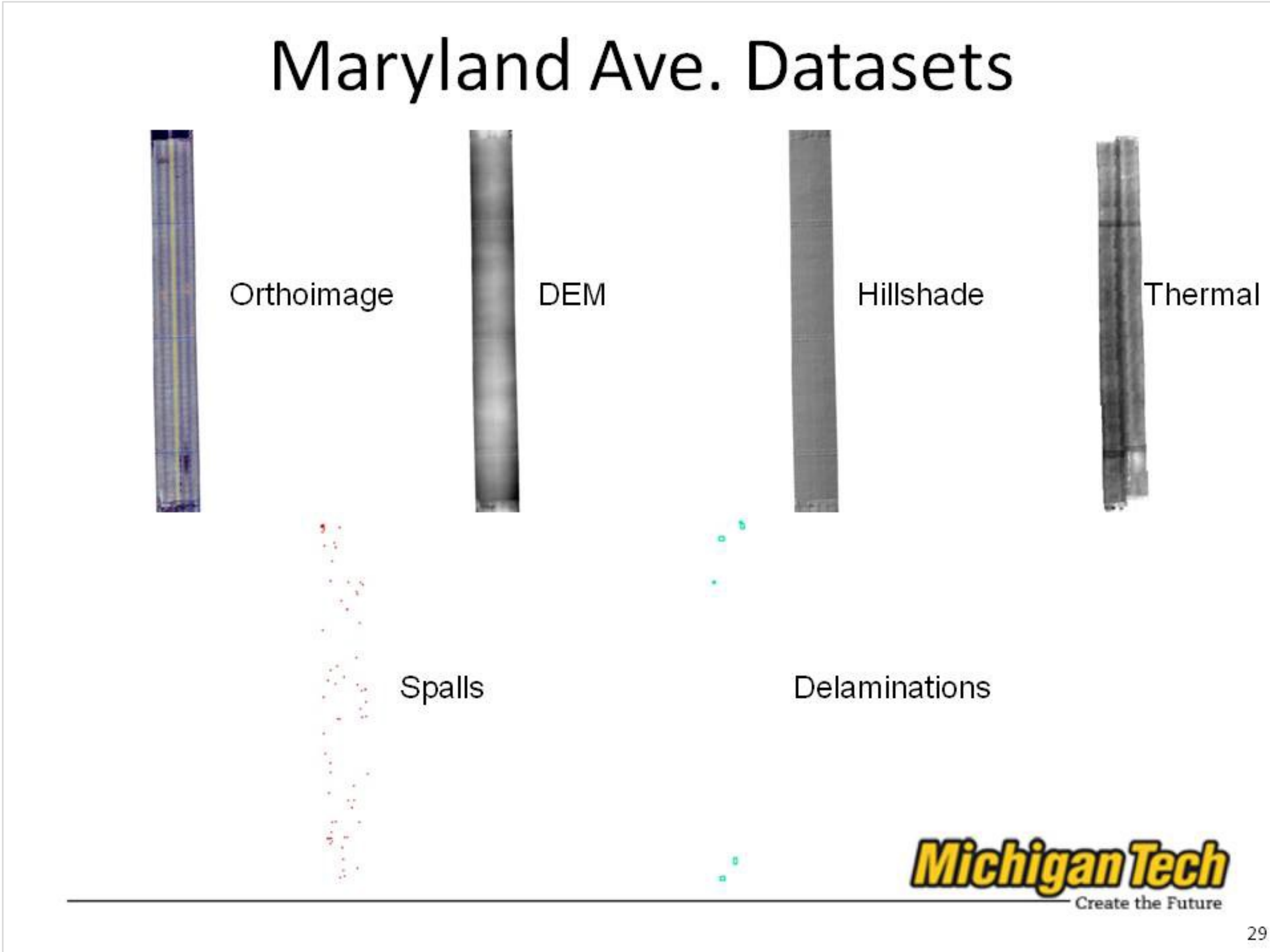

Figure 3: GIS layers created from 3-D photogrammetry and thermography.

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).

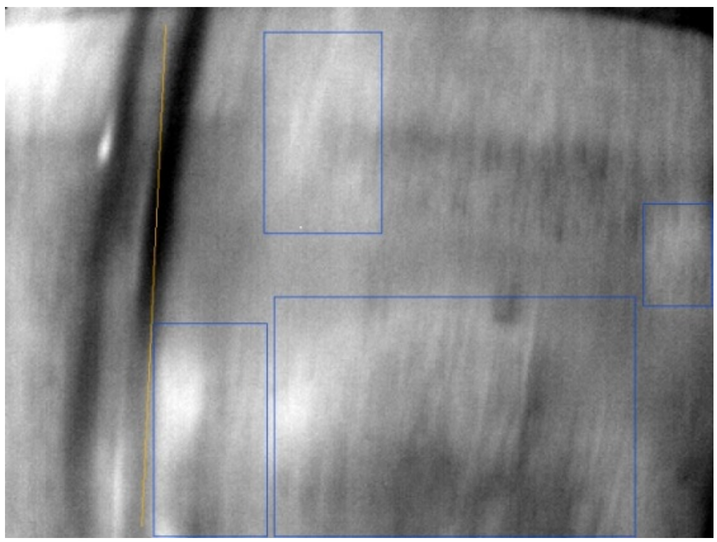

Figure 4: Passive thermal imagery was processed and analyzed for the detection of potential delaminations (blue boxes).

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).

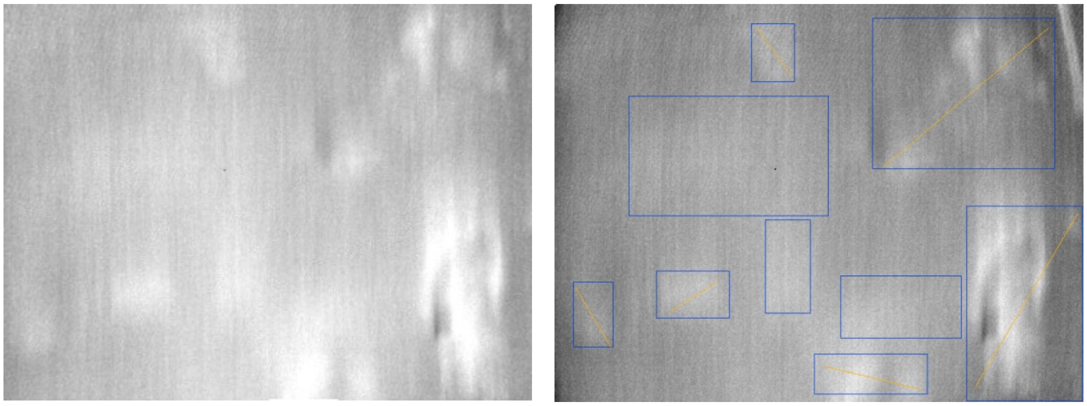

Figure 7: Raw thermal imagery (left) and thermal imagery processed to highlight areas of potential delamination (right).

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 16th.

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.

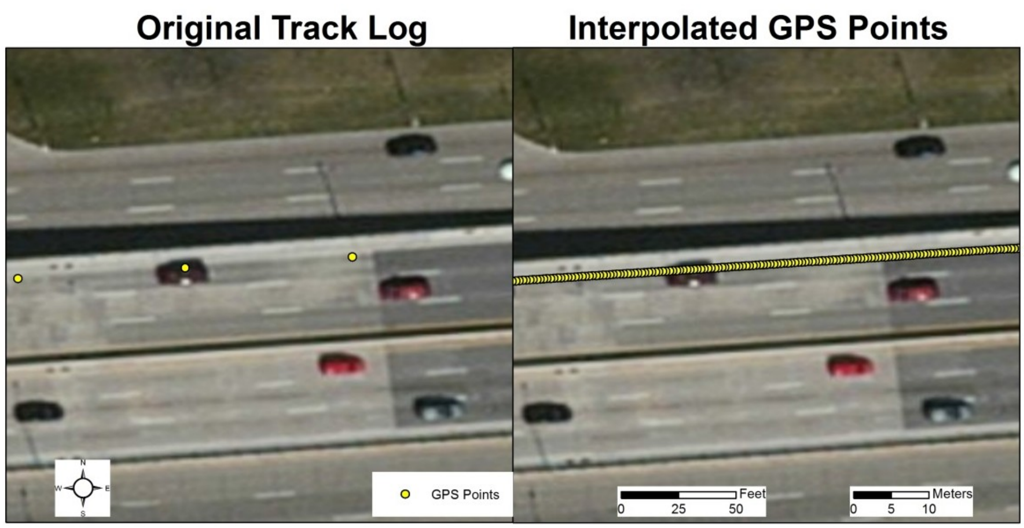

Figure 14: 8 Mile Rd with original and extracted GPS points for the westbound right lane pass.

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.

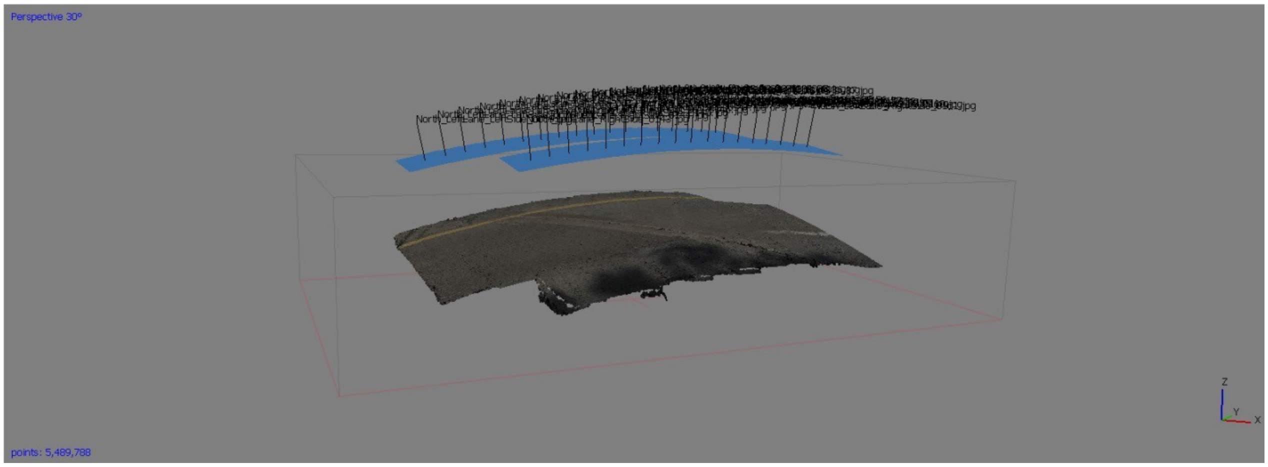

Figure 15: Example of I-75 point cloud demonstrating the reconstruction challenges encountered.

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.

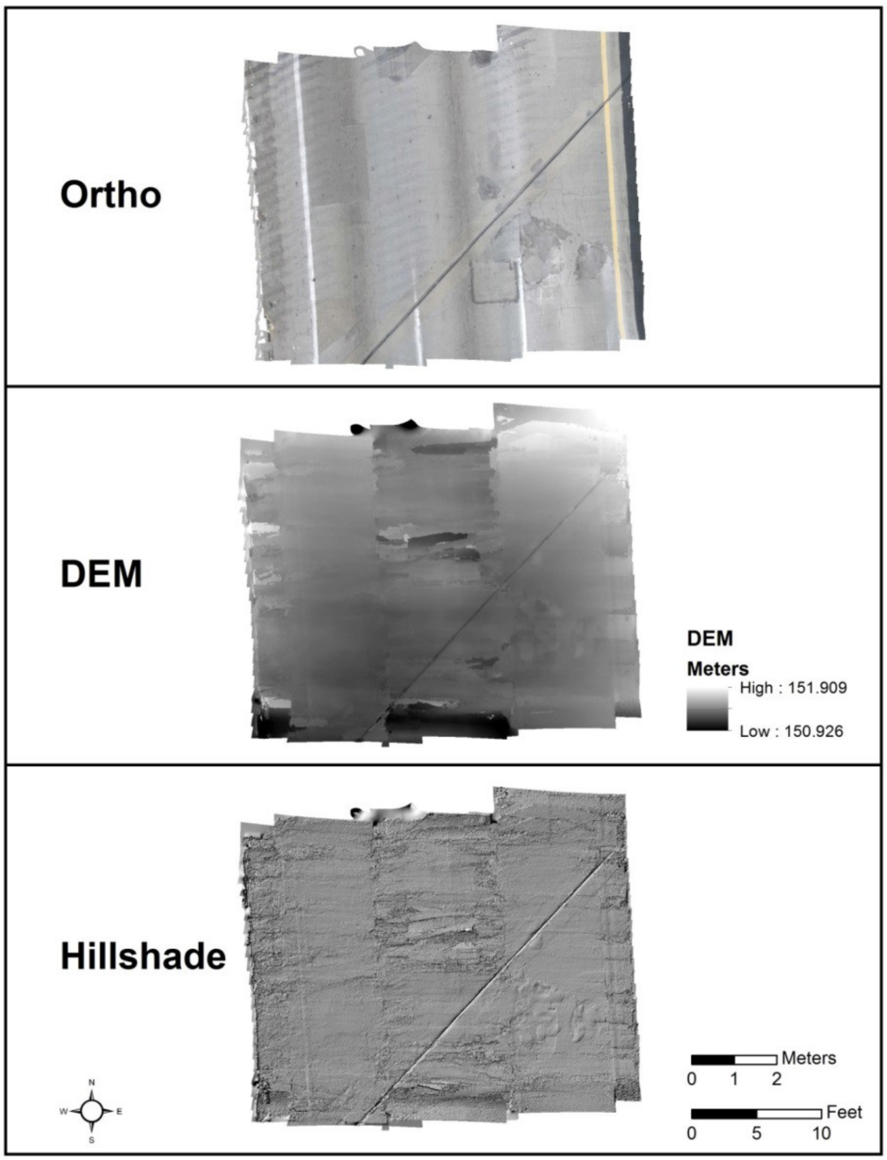

Figure 16: A roughly 20 ft section of I-75 SB processed through Agisoft using geotagged imagery and orientation parameters.

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.

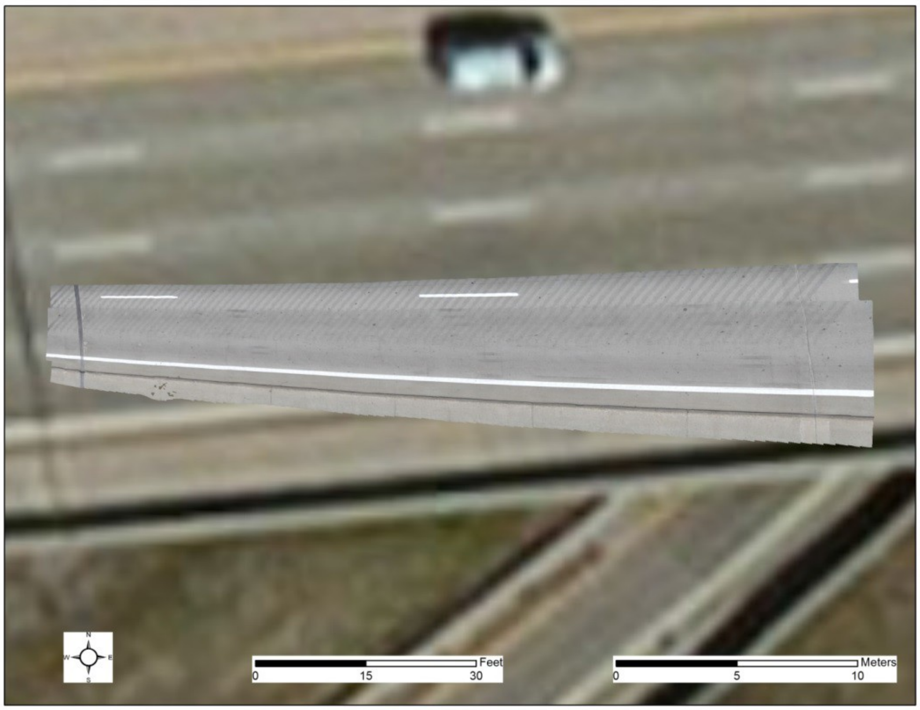

Figure 17: A section of I-696 modeled in Agisoft using geotagged RED imagery and camera orientation information.

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).

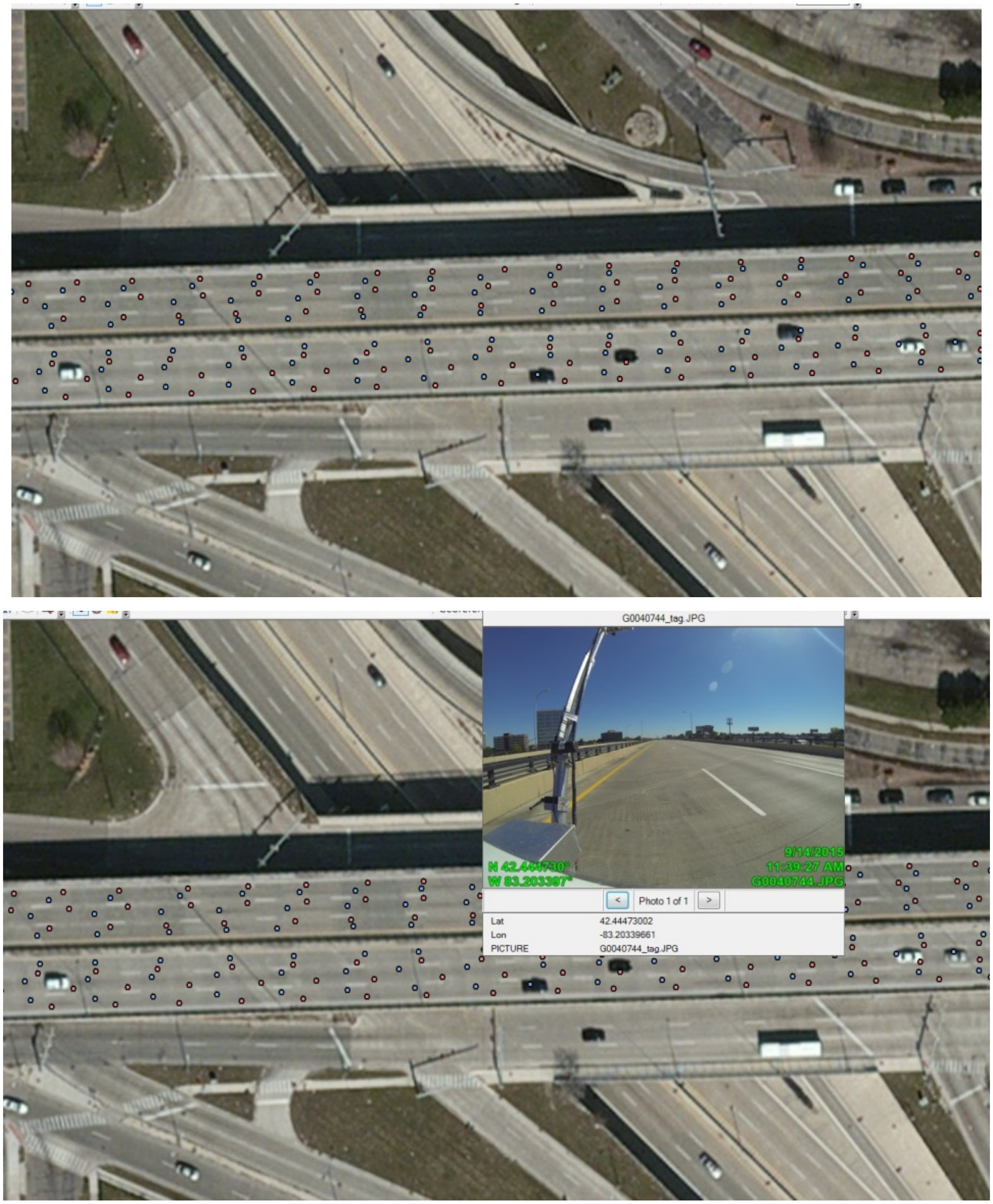

Figure 18: A subset of the 8 Mile Bridge with BVRCS GPS data placed on the bridge (top) and the image showing the bridge deck section that corresponds to the GPS data point (bottom).

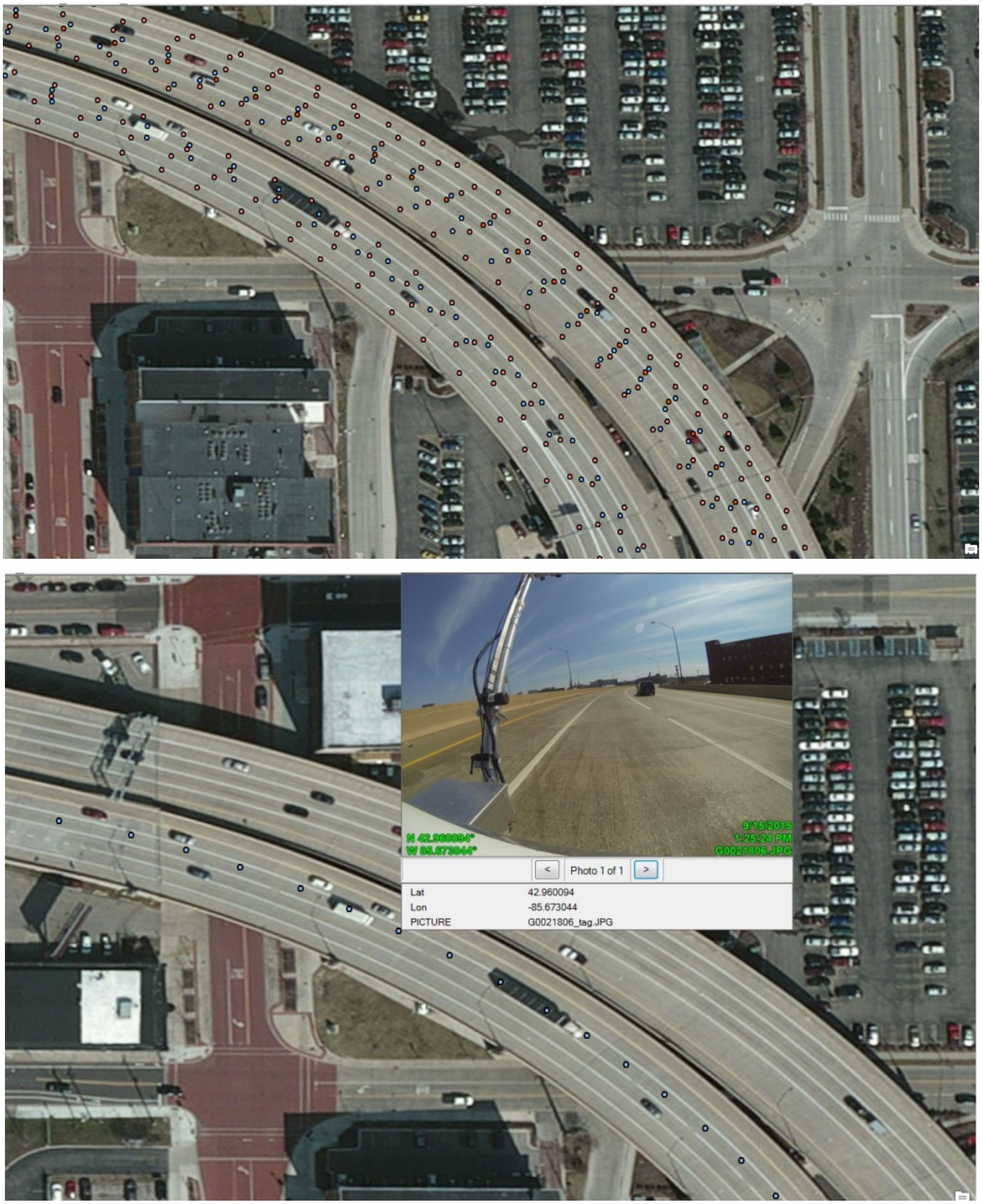

Figure 19: A subset of the US-131 NB/SB Bridges with BVRCS GPS data placed on the bridge (top) and the image showing the bridge deck section that corresponds to the GPS data point (bottom).

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).

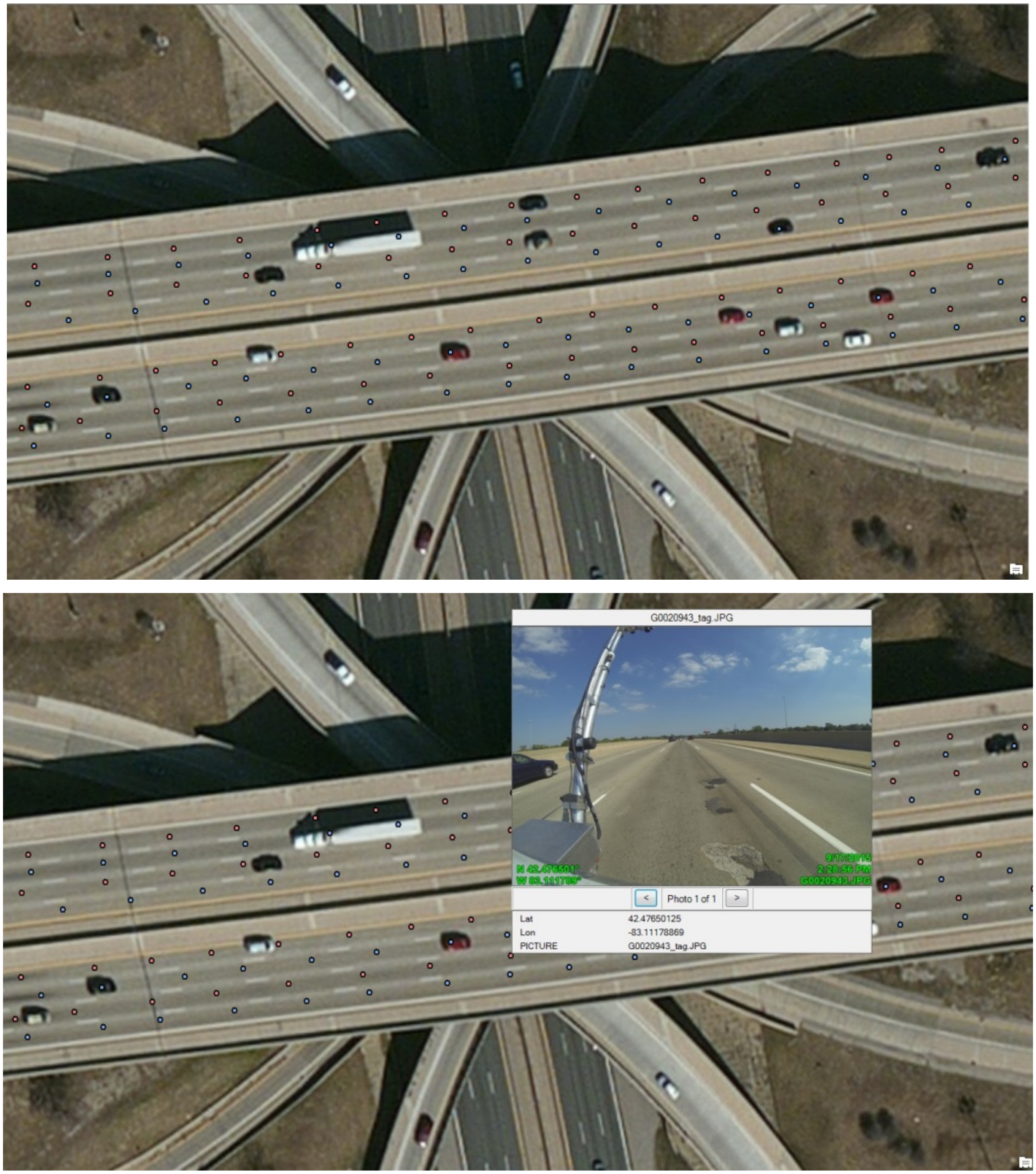

Figure 21: A subset of the I-696 Bridge with BVRCS GPS data placed on the bridge (top) and the image showing the bridge deck section that corresponds to the GPS data point (bottom).