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INTEGRATED REMOTE SENSING AND VISUALIZATION (IRSV) SYSTEM FOR TRANSPORTATION INFRASTRUCTURE OPERATIONS AND MANAGEMENT

-PHASE ONE-

VOLUME 5

Automated Management Bridge Information System

by

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USDOT Report Number 01221
September 2010

REVISED

Technical Report Documentation Page

1. Report No USDOT/RITA DT0S59-07-H-005	2. Government Accession No.	3. Recipient Catalog No.

4. Title and Subtitle INTEGRATED REMOTE SENSING AND VISUALIZATION (IRSV) SYSTEM FOR TRANSPORTATION INFRASTRUCTURE OPERATIONS AND MANAGEMENT: PHASE ONE, VOLUME FIVE, AUTOMATED MANAGEMENT BRIDGE INFORMATION SYSTEM	**5. Report Date** December 2009 **6. Performing Organization Code** UNCC 551356/501356
7. Authors Zhenghui Hu Ronald T. Eguchi Howard Chung	**8. Performing Organization Report No.** 12-31-2009
9. Performing Organization Name and Address ImageCat Inc. USA 400 Oceangate Ste. 1050 Long Beach, CA 90802	**10. Work Unit No.** **11. Contract or Grant No.** **DT0S59-07-H-005**
12. Sponsoring Agency Name and Address Research and Innovative Technology Administration USDOT 1200 New Jersey Avenue, SE Washington, DC 20590	**13. Type of Report and Period Covered** Final Report; June 1, 2007 through December 31, 2009 **14. Sponsoring Agency Code**

15. Supplementary Notes

16. Abstract

This volume focuses on one of the key components of the IRSV system, i.e., the AMBIS module. This module serves as one of the tools used in this study to translate raw remote sensing data – in the form of either high-resolution aerial photos or video from a ground-based mobile data collection system – into indices that help to quantify the performance state of a bridge. Two major performance conditions are analyzed: the condition of bridge deck surfaces and the amount of separation between bridge deck spans. Both of these performance measures can identify conditions that could adversely affect the performance of a bridge. And both conditions, if not mitigated, could become worse with time. Although developed as a separate module, the plan in Phase II is to fully integrate AMBIS into the IRSV system. The results presented in this volume represent our "proof-of-concept" that remotely-sensed data can indeed be used to identify potential distress conditions for bridges. While further research is recommended to help refine the distress state rating procedures outlined in this volume, we feel that the results are compelling enough to warrant their incorporation into the IRSV system as representative indicators of bridge performance.

17. Key Words Bridge Management Systems, Infrastructure Management Software, Image processing, Pattern recognition, GIS, Remote Sensing, High resolution aerial imagery	**18. Distribution Statement** Unlimited distribution

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No of Pages	22. Price
Not classified	**Not classified**	45	

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE **PAGE**

LIST OF TABLES

Executive Summary

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5.1. INTRODUCTION

This volume focuses on one of the key components of the IRSV system, i.e., the AMBIS module. This module serves as one of the tools used in this study to translate raw remote sensing data – in the form of either high-resolution aerial photos or video from a ground-based mobile data collection system – into indices that help to quantify the performance state of a bridge. Two major performance conditions are analyzed: the condition of bridge deck surfaces and the amount of separation between bridge deck spans. Both of these performance measures can identify conditions that could adversely affect the performance of a bridge. And both conditions, if not mitigated, could become worse with time. Although developed as a separate module, the plan in Phase II is to fully integrate AMBIS into the IRSV system. The results presented in this volume represent our "proof-of-concept" that remotely-sensed data can indeed be used to identify potential distress conditions for bridges. While further research is recommended to help refine the distress state rating procedures outlined in this volume, we feel that the results are compelling enough to warrant their incorporation into the IRSV system as representative indicators of bridge performance.

A significant driver in this research has been the mounting costs associated with the repair and maintenance of U.S. infrastructure systems. While the analysis of roadways and bridges has been paramount in the last several decades, the incorporation of advanced and emerging technologies to facilitate rapid and more effective evaluations has been slow. When one considers that roughly $54 billion a year are spent by the public for vehicle repairs caused by poor road conditions (ASCE, 2005) and that government expenditures to repair, maintain and preserve deteriorating roads are estimated to be well over $50 billion a year, it is imperative that roadway and bridge maintenance programs at all levels of government be developed that will exploit the emergence of new technologies that will help to better prioritize and implement infrastructure maintenance programs.

The research team for this study has been addressing infrastructure performance for well over several decades. One particular effort, which is especially relevant to this study, is the analysis of pavement performance. With initial funding from the National Science Foundation, members of the current research team developed a sophisticated software program that automatically measures the distress state of pavements using data collected from video streams (Chung and Shinozuka, 2004). This software – entitled AMPIS for Automated Management Pavement Inspection System – was augmented in this study to also allow an examination of bridge deck surfaces. Specifically, two major enhancements were made: 1) modification of AMPIS so that it could serve as a "ground-truth" data collection tool – collected data/images would be used to compare interpreted images from high-resolution aerial imagery to actual ground conditions, e.g., distressed bridge surfaces, and 2) adjustment of image processing algorithms within AMPIS so that critical bridge distress conditions (such as joint separations) can be distinguished from other non-structural artifacts (e.g., shadows, debris, etc.) in high-resolution aerial images. With these modifications, AMPIS (Automated Management Pavement Inspection System) was renamed AMBIS which stands for *Automated Management Bridge Information System*.

AMBIS has three major components: a data acquisition module, a core analysis component, and a data management component. The integration of these components allows a user to determine two distinct damage measures for bridges. The first measure – like AMPIS – deals with the distressed state of the bridge deck surface. Modifications were made to the underlying AMPIS software so that a broader range of surfaces and distress states could be detected and analyzed in AMBIS. The second measure focuses on bridge deck separations. Using very-high resolution aerial images, AMBIS is able to estimate the separation between joints on multi-span bridges. Over time, this ability to monitor and track changes in joint separation could be used to identify potentially unsafe conditions associated with bridge spans. In addition, the rate of deterioration can be tracked and monitored. Section 5.2 discusses in detail the various components that make up AMBIS. Some of the key steps addressed in this discussion include data collection system, data processing, geo-referencing, image analysis, image enhancement, feature extraction, and aerial image analysis. In addition, a detailed discussion of distress indices (with examples produced for a number of bridges located in North Carolina) is provided.

This volume consists of four sections, including this introduction. Section 5.2 introduces the various AMBIS components, focusing on the data collection system, image processing algorithms, the computation of deck distress indices, and integration into the IRSV system. Section 5.3 presents the study results. We provide results for both deck distress caused by damage to the bridge deck surface and distress caused by joint separations between bridge spans. Section 5.4 presents a brief discussion of current limitations of the analysis and recommendations for future research.

5.2. AMBIS COMPONENTS

5.2.1 Overview

The conceptual framework for AMBIS is illustrated in Figure 5-1. Like its predecessor (AMPIS), the system architecture is comprised of three distinct levels: data acquisition, core analysis, and data management. The three levels allow a user to collect raw images (video or photos) from the field, to process and analyze this information so that bridge distressed states can be effectively identified, and to easily present the results of the analysis through a data management interface.

The *Data Acquisition* level is comprised of three specific data collection components: video camera, GPS technology, and remotely-sensed imagery (i.e., high-resolution aerial imagery). The video camera allows high-resolution field data to be collected on bridge deck surfaces, as well as on approach structures (e.g., ramps, abutments, etc.) leading to the bridge. This field data – in the form of continuous video or extracted photos – is geo-referenced using a GPS receiver. The remotely-sensed data corresponds to the aerial photographs captured during fly-over deployments (with a spatial resolution on the order of centimeters). Note that in the case of monitoring changes to bridge decks over time, multiple, time-sequenced images are required.

The *Core Analysis* level consists of four major components: a geo-referencing tool, an image processing algorithm, a bridge management module, and a reporting system. The geo-referencing tool links raw images and GPS coordinates stored during data collection deployments to create a trail of locations from where each image sequence is produced. This trail is displayed within an AMBIS mapping-interface, allowing easy identification of problematic sections of the bridge. The image processing algorithm is designed to translate geo-referenced images into a set of vectors which characterize the surface features of a bridge deck in order to determine distress conditions and provide an overall rating (e.g., U.S. Army, 1982). For example, Figure 5-2 **Figure 5-2 Image Processing Steps within AMBIS** illustrates how surface distress is identified. The first image contains the raw road surface image, the second image displays an intermediate image showing cracks identified by using edge detection algorithms, and the last image illustrates the process of identifying and classifying road cracks. The length and pattern of these tracks are used to determine the distress conditions of the road surface.

The final distress determination is integrated into an AMBIS report that contains both estimated distress states and distress types which can range from simple cracks to more extensive distress, such as potholes and other compression failures. The AMBIS report feeds into the bridge management component, which allows the processed images to be linked to other key bridge information, such as year built, physical dimensions of the bridge, bridge deck skew angles, number of columns, etc. In a larger context, this information will eventually be housed in module that is part of the IRSV system.

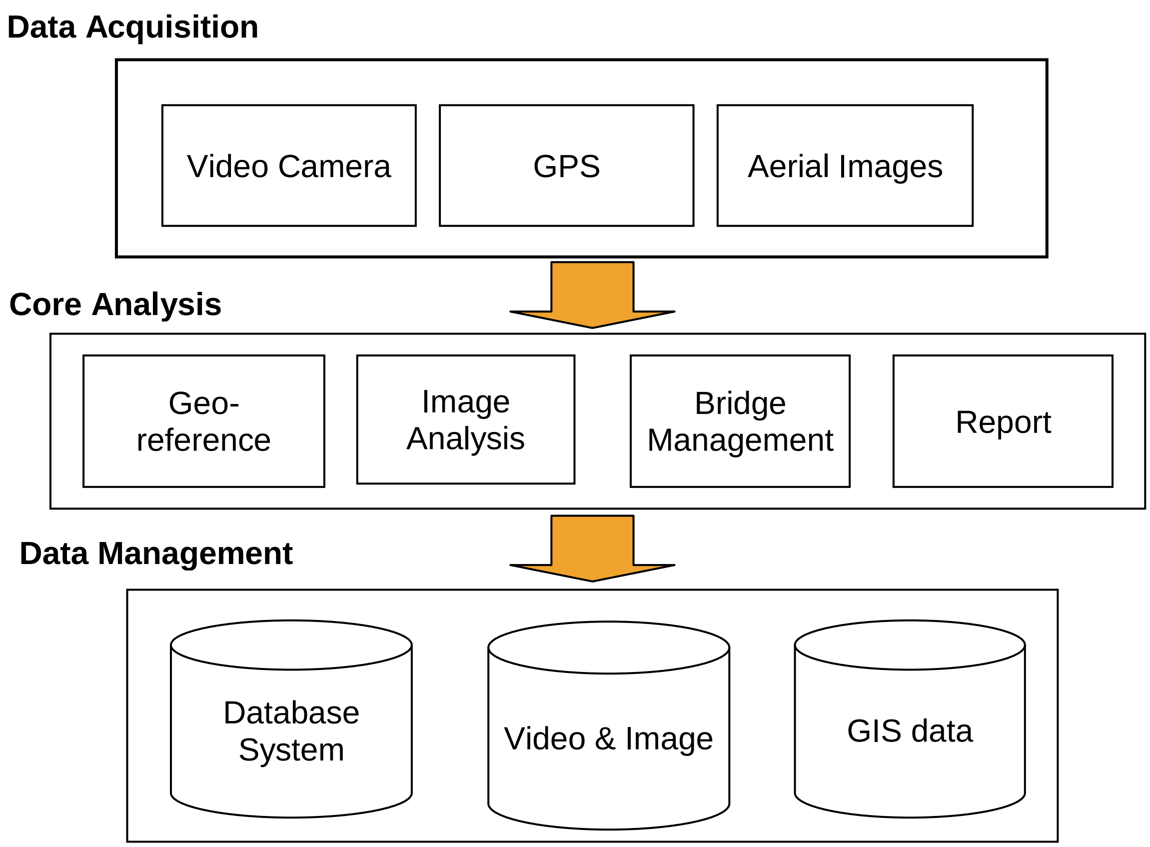
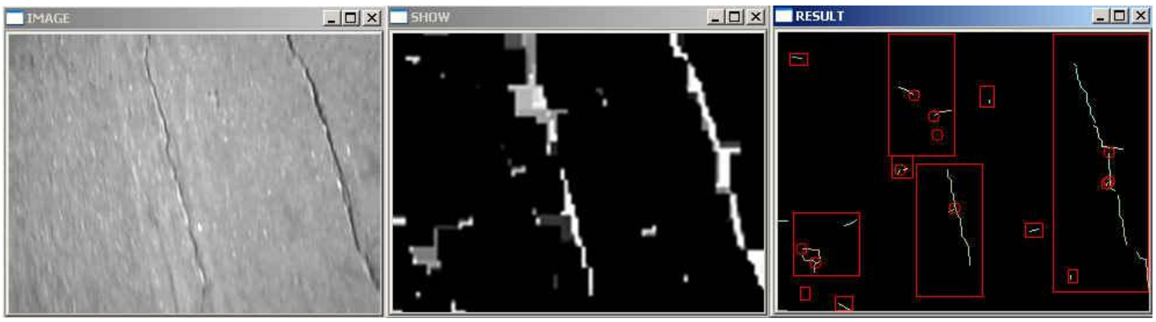


Figure 5-1 System Architecture for AMBIS

The last level is the *Data Management* layer. In this layer, we produce information that can be directly imported into the IRSV system. Currently, the data formats include database elements (in the form of Microsoft Access Database), images (both video and still) and GIS data (locations of bridges and GPS trails identifying where images were captured). The information in this layer can be used by bridge management personnel to evaluate the distress state of all bridges in the system. When combined with information on costs to repair or maintain, and the rate of distress over time, AMBIS can be used to prioritize repairs and maintenance activities based on available budgets. All of these features will be integrated directly into the IRSV system.

The following subsections discuss in more detail the specific components that make up the AMBIS system.



a) Raw Image **b) Edge Detection** **c) Feature Extraction**

Figure 5-2 Image Processing Steps within AMBIS

5.2.2 Data Collection System

The AMBIS software has been designed so that a data collection tool resides directly within the system. Although the software can import data from videos, the preferred method for developing a data stream is to conduct an AMBIS data collection deployment.

The hardware requirements for setting up AMBIS for data collection are 1) a laptop computer, 2) a GPS unit connected through serial port, and 3) a video camera installed and connected to the computer through either a USB or Firewire interface. For an extended deployment, an AC-DC converter is recommended in order to charge the laptop battery while driving from bridge to bridge.

The camera for the AMBIS data collection system is normally mounted on the back of a vehicle. In order to minimize large movements, the camera is connected to a tripod which is mounted on a rack or the roof of the vehicle. For more consistent data, it is recommended that an externally-controlled light source illuminating the bridge deck surface be used while imaging. This can significantly reduce the effect of shadows which can adversely affect any image processing. Unless a high-speed camera is used to collect the images, it is recommended the speed of the vehicle should be 25-30 mph or less in order to minimize the amount of blurriness in the images.

The collection system must be started/paused/stopped manually, so at least two people are needed; one person driving the vehicle and another person operating the AMBIS system. The AMBIS system operator must prepare for the deployment by setting up the project within the AMBIS software and completing the inspection description form. The operator must then calibrate AMBIS with the GPS unit to make sure the correct latitude/longitude coordinates are being read into the system. The AMBIS interface will automatically center the main map to the current location, allowing easy verification of the starting point. Once the camera is turned on, the operator must adjust the brightness and contrast levels for the camera and specify the sampling interval in milliseconds (the system works best if the sampling rate is less than 20 frames per second). At this point, the system is ready for data collection.

For comprehensive coverage, it is recommended that the vehicle cover one lane at a time. At each sampling point, a new image of the bridge deck surface is captured, and a GPS reading is noted. Both pieces of information are stored in the internal AMBIS database. A log file is then created for the entire set of images collected for that bridge. In case of software or database failure, it is strongly recommended that the time/position/image relationship be retained. The above process is repeated for each traffic lane on the bridge until all lanes have been imaged.

5.2.3 Data Processing

Each bridge inspection produces many images with their associated longitude/latitude coordinates. This data is then processed within the 'core analysis' module to identify potential distress features from the images. This information is used to classify possible damage or distress states and to eventually produce a deck distress rating. The results of the analysis can be visualized using the GIS user-interface, and a report can be printed or exported as an XML file which is then incorporated into IRSV system. The following subsections discuss in more detail the specific tasks that are performed during the data processing step.

5.2.4 Geo-referencing

During the deployment, a GPS receiver and camera are always attached to a computer. As part of this process, the camera continually captures images and sends this information to the core analysis module where AMBIS requests a GPS reading from the receiver and associates the GPS coordinate to that image.

A GPS reading, however, does not always guarantee that the exact location of where the image was captured will be registered within AMBIS. GPS readings are highly dependent on the quality of signals received by the GPS unit from available satellites. If the satellite signals deteriorate during any part of the data collection process, the same latitude/longitude coordinate might be read and carried over to other points along the deployment route. For most applications, this small latency does not cause a big problem, especially if you are driving in a straight-line direction, or the difference between the middle of the bridge or ¾ of the way across does not make much difference. But within AMBIS, each GPS reading is attached to a particular image and is supposed to be the exact location of the image. So, there should not be multiple images associated with the same coordinate. In order to avoid this possible problem, a post-processing algorithm is needed to ensure that each image has a distinct geographic coordinate.

In cases where many photos share the same latitude/longitude coordinate, only the first reading is considered accurate. In AMBIS, inspection data are all associated with a particular bridge, which is likely to be part of a street segment. So the geometry of that street provides a reference line to adjust the coordinates for that bridge. The coordinate of the first photo is kept intact, while all other coordinates are interpolated and shifted along the street segment following all the turns of the street geometry.

5.2.5 Image Analysis

A digital image is just a collection of pixels where each pixel represents some intensity level of red, green and blue. So to the computer, an image is just a large matrix of intensities. Image processing techniques consists of information extraction algorithms that can process this matrix and extract specific patterns. This process is usually separated into pattern extraction and pattern classification schemes.

In AMBIS, the patterns of interest are cracks, which are mostly line features. The pattern extraction steps are:

1. Image enhancement,
2. Edge detection and thinning, and
3. Feature grouping

5.2.6 Image Enhancement

The goal here is to eliminate excessive noise while at the same time enhancing the linear features of a crack. The steps involved in image enhancement are 1) the incorporation of smoothing techniques to eliminate the noise; and 2) the use of histogram equalization techniques to sharpen the features of the crack.

In image processing, *noise* usually refers to the random variation of color intensity in an image, where the source of the variation is usually attributed to the camera. The presence of noise can often lead to 'false positive' classifications during the pattern recognition process, and should be minimized to the greatest extent possible without altering the original image.

Gaussian smoothing techniques are often used to reduce noise. The Gaussian smoothing algorithm is a type of image-blurring procedure that uses a Gaussian function to calculate a new value for each pixel in an image. In this process, the Gaussian function is applied as a filter to every pixel, sometimes referred as a transformation kernel. The result of applying the filter is a "weighted average" of each pixel's neighborhood, with the average weighted more towards the value of the central pixels. The Gaussian filter provides a gentler smoothing of the image and is able to preserve edges more effectively than mean filters.

Histogram equalization is a technique to redistribute the intensity level of a grayscale image, effectively modifying the lightness, darkness, or contrast. First, a histogram is created of the grayscale values from 0 to 255 (0 corresponding to black, and 255 corresponding to white). If the histogram is negatively skewed, the image appears dark to the eye, positively skewed histograms correspond to bright images, histograms with high kurtosis appear low contrast, and low kurtosis appear high contrast. From the original histogram, a separate "equalized" histogram is created with a grayscale mapping for which the eye is able to identify more detail. The original histogram is "mapped" onto the equalized histogram, by adjusting a best-fit bell-curve distribution. A lookup table is produced, and the grayscale values are replaced with the transformed values. Histogram equalization changes the grayscale value used to display the image, but conserves the relative distribution of pixel-values and thereby retaining the content. So, even though every value in an image may change, the captured data may become more suitable for detecting detail.

This technique is useful in the analysis of bridge deck distress because most bridge deck images have a limited range of colors/intensity, i.e., crack features are usually just shades of gray darker than the surrounding deck background. Applying a histogram equalization process to these images enhances the delineation of the crack thus allowing for better detection.

5.2.7 Feature extraction

Here the goal is to extract crack features from the image in a vector format. The vector can then be imported for analysis using various classification or rating schemes. The steps involved are: Laplacian edge detection, thinning and vectorization.

Laplacian edge detection algorithm. The Laplacian edge detection algorithm uses the 2nd spatial derivative of an image to detect regions of rapid intensity change (edges). It is highly sensitive to noisy images, but the application of a Gaussian smoothing filter helps to reduce the noise in the image.

The Laplacian *L(x,y)* of an image with pixel intensity values *I(x,y)* is given by:

$$L(x,y) = \frac{\partial^2 I}{\partial x^2} + \frac{\partial^2 I}{\partial y^2}$$

In the actual implementation of this process, it is common to use discrete convolution matrices (kernels) to approximate the derivatives. For example, the figure below presents one four-connected kernel at the left and one eight-connected kernel to the right.

0	−1	0
−1	4	−1
0	−1	0

−1	−1	−1
−1	8	−1
−1	−1	−1

When the four-connected matrix is applied during the convolution process, each pixel in the image is assigned a new value according to the values held by its four direct neighboring pixels. The eight-connected matrix is applied in the same way, only this time all eight of its neighbors contribute to the final pixel value. The new value at current pixel can be positive or negative, and the zero-crossing points are the candidate edge points. The edges found in the image represent potential crack features.

Thinning. Thinning refers to the process of reducing the number of points needed to define a line feature while preserving the essential shape of the line.

For AMBIS, this 'thinning' algorithm is represented by an iterative process that removes pixels that are on the edge of the line, and transforms thick lines into thinner lines in preparation for vectorization. At each iteration, a two-pass 'mark and remove' process is applied. The 'mark' pass attempts to match 46 filters to each pixel and its surrounding neighbors, and marks each matching pixel in order to remove pixels. The 'remove' process uses another set of 69 filters to remove more pixels. This process is repeated until no more pixels match these filters.

Vectorization. Vectorization refers to the process of grouping pixels into lines and locating intersection points. The line tracing algorithm is an iterative process; it starts by examining the top-left corner of an image, and proceeds from left-right, and from top-bottom. First, the starting point of a line is located and then each of its neighboring pixels is examined. One of the following conditions may occur: 1) there is no non-zero neighbor, in which case, the line ends - the next starting point then needs to be located, or 2) there is one non-zero neighbor, in which case the line continues on to the neighboring pixel and the process is repeated, or 3) more than one neighboring pixel has non-zero value. In this case, this point is marked as an intersection point.

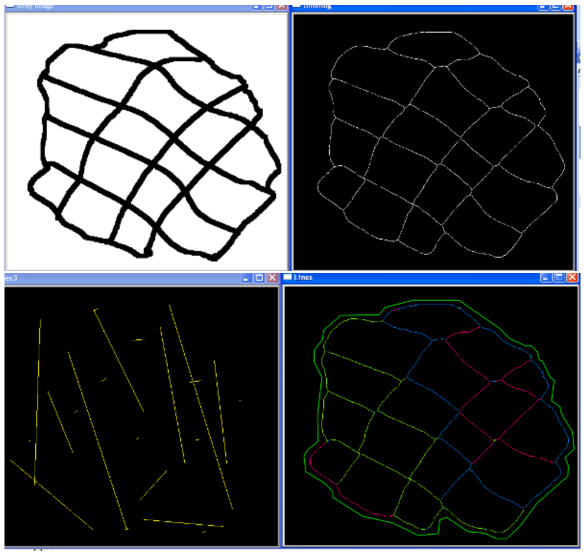
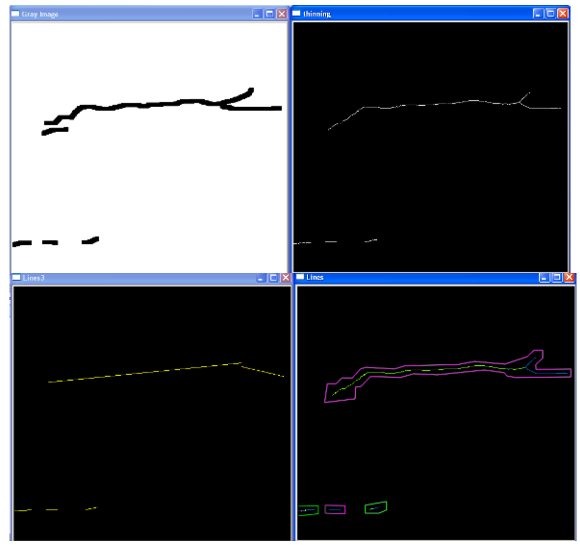
If two detected lines have end points that are within a pre-determined threshold, they are connected together into a single line. This is done because sometimes, during the noise reduction/edge detection steps, there are pixels that are mis-classified or eliminated as a side effect of this algorithm.

Feature classification. In AMBIS, a decision tree based feature classification scheme is used to classify cracks. This heuristic approach is based on observations and earlier statistical analysis of crack features. An earlier attempt to use an AI (artificial intelligence) classifier did not produce good results, i.e., the amount of false positives was found to be unacceptably high. In AMBIS, several different parameters are used to identify possible distress features:

- *Contour*: representing the envelop containing connected lines,
- *Area*: the number of pixels before thinning is applied,
- *Vectors*: thinned lines representing the cracks, and
- *Intersection points*: points connecting multiple crack lines into a large crack feature

Error! Reference source not found.illustrates the difference in the attributes associated with wo types of damage states.

Table 5-1 Possible Damage States

Alligator cracks	Line cracks
	
One contour has many lines **Contour area is large** **Regressive curve has a larger deviation** **Many intersection points for lines.**	**One contour contains only few lines.** **The contour is narrow.** **Regressive curve has the least deviation** **Very few intersection points for lines.**

Based on these observations, a final decision tree was developed – see Table 5-2.

Table 5-2 Vector Tree – Classification of Distress States

Vector Trees

Classification of Distress

A.	Group Rect >50%				
A.1	Group Area>45% of Group Extent				Suspicous of alligator cracks
		Ratio of Group Area over Thinned Lines			
	A.1.1	>=5	(pixels)	H	Alligator
	A.1.2	<5		M	Alligator
A.2	Group Area < 45% and >=15% of Group Extent				Suspicous of blocking cracks
		Ratio of Group Area over Thinned Lines			
	A.2.1	>=5	(pixels)	H	Blocking
	A.2.2	<5 >2		M	Blocking
	A.2.3	<=2		L	Blocking
A.3	Group Area < 15% of Group Extent				Suspicous of slant longitudinal/tranverse crack lines
		Ratio of Group Area over Thinned Lines			
	A.3.1	>=5	(pixels)	H	Long/Tranverse
	A.3.2	<5		M	Long/Tranverse

5.2.8 Aerial Image Analysis

The high-resolution images collected in this study (via airborne sensor) presented some unique challenges, and ImageCat worked closely with the project's *Structures Group* to determine the best technique for processing these images. The ultimate objective is to provide meaningful metrics to bridge inspectors and/or managers using image processing techniques. These processes should be automated, and should provide robust statistics back to the users regardless of lighting conditions, road conditions, traffic, or weather conditions. The Structures Group identified changes in joint conditions as being the one of the most important indicators of possible damage that may be observable from an airborne platform. And so, the emphasis in this part of the analysis is extracting information on joint separations.

A large separation at the joint might not directly signal a serious damage condition in the bridge's substructure, but it might indicate the need for a cursory inspection at the site by the inspection team.

Because the area of the bridge that would be of concern is small relative to the entire bridge deck, a sampling process – as was done for the assessment of deck cracks – is not necessary. Since the concern with bridge deck separation is more about the structural integrity of the bridge than about surface distress conditions, the distress index developed here should be viewed as a screening factor for more thorough analyses. Also, since the images that are analyzed here cover the entire bridge, it was necessary to modify the image processing algorithms in AMPIS so that a more relevant metric could be developed.

Using high-resolution aerial photos, the bridge deck is captured by a single, large image that is associated with a single latitude/longitude coordinate. The AMBIS analysis module only utilizes the bridge deck portion of the photo to generate the joint separation analysis results. The bridge deck joint analysis looks for features that go across the entire bridge deck and are at least an inch wide.

Algorithms for identifying and quantifying bridge span separations. The overall process is comprised of two parts: 1) identifying or locating the joints, and 2) estimating the amount of joint separation between bridge deck spans.

The initial steps of smoothing and enhancing that were discussed above also apply to the aerial images. These techniques only need to be applied to a very small area within the image (i.e., where the joints are located).

The approach used to extract joints from the high-resolution aerial imagery is very different from the techniques used to assess bridge deck distress. Because of the size of the aerial image, tracing each feature in an image pixel by pixel using an iterative algorithm is not a feasible solution.

We know in advance that the joints on a bridge should traverse the entire bridge deck width and that they should follow a straight line. So our algorithm for identifying joints must be able to detect straight-line segments that cross through the image. By knowing these two properties (linearity and length), a line detection algorithm based on a *Canny edge* detection and *Hough line* transform were chosen for this task.

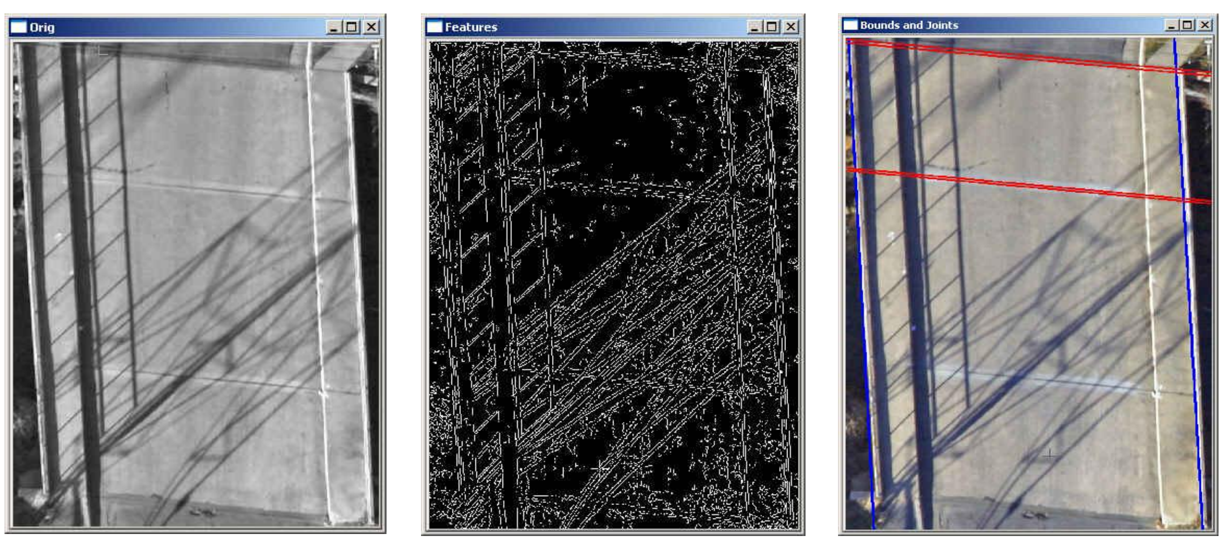
A Canny edge detection algorithm allows the user to set parameters such as the size of a Gaussian filter and pertinent threshold values needed for the analysis. This added flexibility allows more fine-tuning, thus the ability to generate better results. The Hough line transform is a method originally created for finding straight lines in a binary image. During the transformation, it converts the image into a different space, in which each point in the original image is converted to a set of parameters and plotted as lines. Then accumulators are used to determine the amount of overlap for these lines. Local maxima of the accumulators indicate a high probability of a series of points forming into a line. This algorithm will locate many line segments within the image, not only joints but all line features present, even features caused by noise.

Here we take advantage of our prior knowledge that a bridge deck joint should traverse the entire width of a bridge deck. Knowing this, we can pick line segments that only cross the entire deck laterally and that form an angle that is more than 45 degrees with respect to the edge of the bridge.

Once the joint lines are found, we can estimate the amount of separation by simply taking the average or maximum width of the line in pixels and multiplying that number by the pixel resolution of the image.

The preliminary results for one bridge are shown in Figure 5-3. **Figure 5-3 Results produced by Joint Detection Algorithm in AMBIS**

From the original image in Figure 5-3**Figure 5-3 Results produced by Joint Detection Algorithm in AMBIS**
, we are able to extract many different features visible in Figure 5-3b. From Figure 5-3c, we can identify the joints between bridge deck slabs in 2 out of 3 cases.



a) Raw image **b) Results of edge detection** **c) Results of joint detection**

and filtering **algorithm**

Figure 5-3 Results produced by Joint Detection Algorithm in AMBIS

5.2.9 Computation of Deck Distress Indices

As discussed earlier, two separate ratings have been introduced in this study to measure the amount of distress observed on bridge deck surfaces: the amount and type of deck cracking or distress; and the amount of joint separation between bridge spans. Both of these measures could reflect distress states that may impact the long-term performance of a bridge. Together with other distress indices (e.g., insufficient vertical clearances beneath bridges), these measures can be used to rate the overall performance state of a bridge.

In order to measure extent of deck cracking and joint separation, the project team employed various image processing techniques. For deck cracking, the team employed a suite of image processing algorithms initially built for the AMPIS system to measure the type and extent of deck cracking. These algorithms were modified for inclusion in the IRSV system by expanding the types of surfaces considered in the image analysis, e.g., concrete surfaces. For measuring joint separations from very-high resolution aerial imagery, the project team developed a separate set of models that extracted lateral joints from other bridge deck artifacts (e.g., shadows, cars, debris) and measured the amount of separation between spans.

To a large extent, these two distress measures represent independent (i.e., weakly correlated) damage or distress states. As such, the combined effect of these measures must be weighted by the individual impact that each distress state would have on the overall performance of the bridge.

5.2.10 Bridge Deck Cracking

There are currently many different ways of measuring and characterizing surface cracking, much of it documented in literature as part of pavement management research. One method which has been discussed in the literature is the AMPIS technology (Chung and Shinozuka, 2004). Because the developers of AMPIS are part of the research team, it was decided to extract and incorporate the core image processing module in AMPIS for application in the IRSV system. Figure 5-4 provides an abstracted view of how surface cracks are translated into DDIs (deck distress indices).

After a set of bridge surface images are collected, each image is geo-registered and referenced in space. Next, a series of textural and brightness adjustments are made in order to prepare the image for vectorization. Linear features are extracted from the raw image and these are thinned and then turned into a series of vectors or poly-lines (raster data). Once this is completed, the internal image processing algorithm will compute crack lengths and orientations. The surface distress state is then assessed based on crack lengths, I_l and crack area densities, I_l. Deck distress indices (DDI) are then expressed in terms of these parameters. Other parameters - α_i (orientation of each crack) and X_c (location of each crack) - are also computed and recorded to help quantify crack patterns.

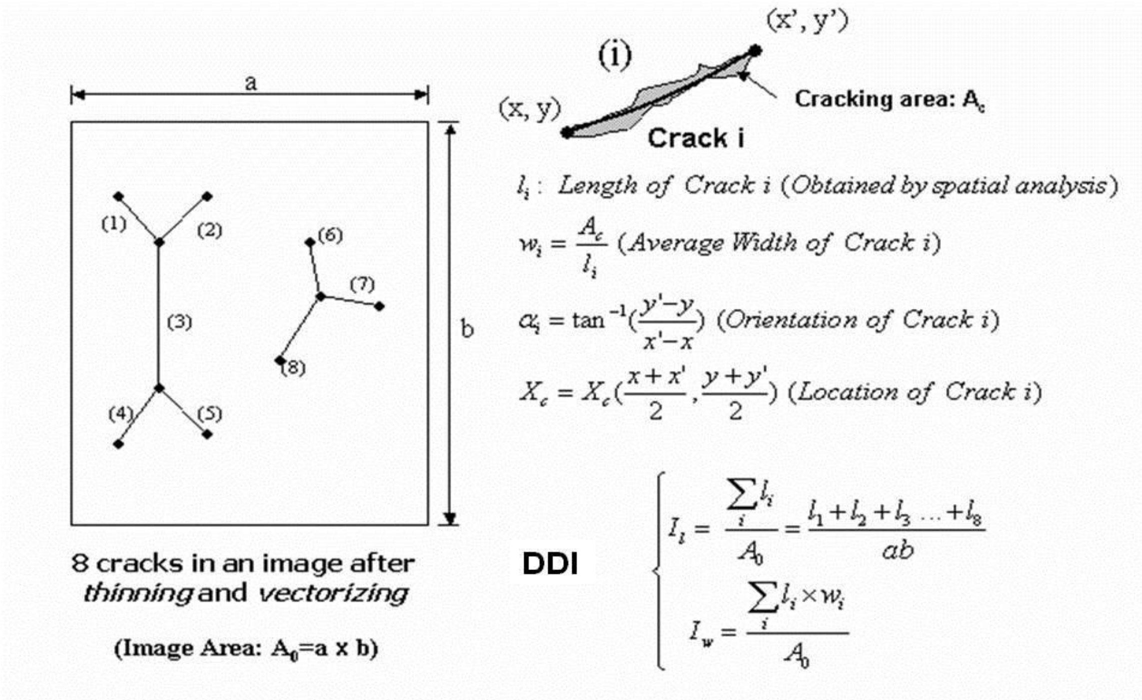


Figure 5-4 Deck Distress Index, DDI

Figure 5-5 shows a DDI rating scale that ranges from zero to 100. This scale has been adapted from the one that is used by the Corps of Engineers in its assessment of pavement performance, i.e., the PMS (Pavement Management System) scale. As in the PMS scale, the higher the rating the better the bridge surface condition is.

Figure 5 - 5 DDI Rating Scale used in AMBIS (modeled after Corps of Engineers PMS scale)

The DDI in Figure 5-5 can also be translated into categories that help suggest whether remedial measures are needed for a particular bridge deck. Using guidelines presented in Kirbas and Gursoy (2010), we have taken these numerical scores and associated them with three remediation categories: adequate (score between 70 and 100), degraded (score between 55 and 70), and unsatisfactory (score between zero and 55). That is,

Distress States	DDI Range	Remediation Action
Failed to Fair	0 to 55	Repair or replacement required
Good	55 to 70	Deterioration, must be monitored
Very Good to Excellent	70 to 100	No remedial action required

Table 5-3 shows several sample images that have been assigned DDI values. These values were computed using the AMBIS software and take into account the type of distress and the distress level or severity (i.e., density of the cracks or distress). In addition, based on the guidelines used by Kirbas and Gursoy (2010), Table 5-3 also suggests whether remedial actions are necessary or not. Note that a more rigorous assessment may be needed in order to determine the type of remedial action that may be required. We hope to make more progress in this area in Phase II of this study.

Table 5-3 Sample Images with DDI Values and Remedial Recommendations

	**Distress Type**	**DDI Value**	**Remedial Recommendation**
	Block Cracking	33	No action required
	**Distress Type**	**DDI Value**	**Remedial Recommendation**
	Linear Cracking (traverse)	100	No action required
	**Distress Type**	**DDI Value**	**Remedial Recommendation**
	Linear Cracking (Longitudinal)	60	Must be monitored

5.2.11 Damage Indices for Joint Separation

Quantifying the impact of joint separations is a multi-step process. First, the extent of separation must be measured by counting the number of pixels that make up the separation between bridge spans. Since the resolution of each pixel in the very-high resolution aerial images is 0.5 inches (or 12.7 mm), the amount of separation is measured in steps of 0.5 inches. The next step is to determine whether the separation of the joint varies along the width of the span. If there is significant variation, then an average or maximum separation is calculated.

To assign a distress rating to the bridge, the project team is using an allowable joint width of 1.5 inches (USDOT, 2006). For example, if the joint separation is less than the allowable width, then the joint is considered good to excellent. If the separation is wider than the allowable width, then the joint is considered average to poor.

In order to translate joint width separations into a rating, we proposed the set of rules in Table 5-4. The efficacy of these ratings will be evaluated and tested as part of the validation process in Phase II. Therefore, these ratings and the method used to calculate them is considered tentative and subject to change. The important point here is to provide a 'strawman' scheme for developing a damage index based on joint separations.

Table 5-4 Numerical Ranking of Joint Separations (Proposed - to be tested in Phase II of this Project)

Joint Separation	Qualitative Rating	Numerical Rating
0.5 to 1 inch	Excellent	80 to 99
1 inch to 2 inches	Good	60 to 80
2 inches to 3 inches	Average	40 to 60
greater than 3 inches	Poor	20 to 40

5.2.12 Integration with IRSV System

The AMBIS software has been designed as a standalone application to be installed on a computer with a Windows XP operating system. AMBIS has been developed to collect large sets of geo-referenced images during a single deployment, and to efficiently analyze that data it is recommended that both tasks (i.e., data collection and analysis) be performed using the same computer. Therefore, it is strongly recommended that a laptop computer be used as the AMBIS platform.

The following are the minimum hardware requirements or specifications necessary to install and use the AMBIS software:

- Pentium 500-megahertz (MHz) processor or faster
- 512 megabytes (MB) of RAM

- 100 megabytes (MB) of available space on the hard disk. Note: this is only for the application. Each AMBIS data deployment and analysis could potentially use up to 1 gigabyte of disk space.
- In addition to above requirements for the computer system, a video camera and a GPS unit is required for data collection.

Video camera requirements

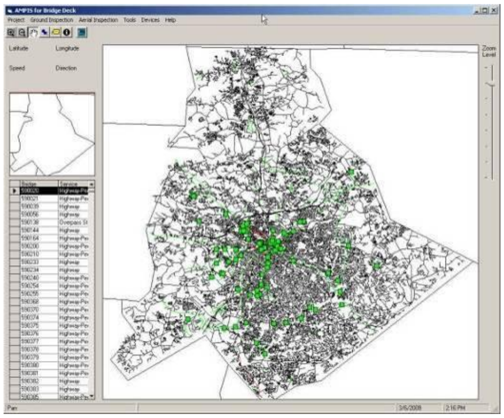
AMBIS uses Microsoft DirectX technology to connect and interact with the camera. This approach allows many options when selecting the camera for use. The video camera must be connected and configured in Windows XP before it can be detected and used by AMBIS. Most commercial-off-the-shelf cameras have the capability of being configured in Windows XP and will provide a video feed into the computer. USB and firewire (IEEE 1394) are the most common interfaces used to connect a camera to the laptop. Once connected, most cameras can be automatically detected and configured by Windows XP with only limited user intervention required.

GPS requirements

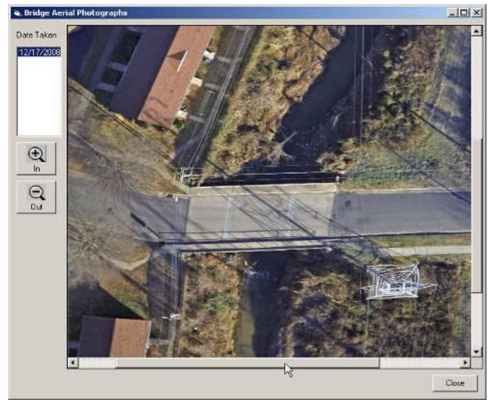
AMBIS reads NMEA messages generated by GPS units that connected to the computer through serial port. NMEA is a data communication protocol controlled by the National Marine Electronics Association; this protocol is implemented by most GPS manufacturers as an output data transmission format. This message format is transmitted to the computer through a serial port only. Thus, only those GPS units that have serial output interface are compatible with AMBIS.

In Phase I of this study, ImageCat worked closely with the project's *Knowledge Group* to create a database link between the IRSV data model and the AMBIS internal database system. Common elements of the *bridge* database are now shared between IRSV and AMBIS. The AMBIS workflow was revised so that when a user defines a project to collect or import data, all of the data are linked by the unique bridge identifier. This effectively allows a very tight integration between the two systems without sacrificing the flexibility and modularity of AMBIS.

Several changes were made to the AMBIS user interface to accommodate system integration and the modified work flow. The overall user interface was adjusted to provide a more map-centric look and feel (Figure 5-6), additional GIS data to support displaying bridge data, and lastly, changes to the dialog boxes that help to create and manage projects and collect field inspection data. In addition, we have also added a visualization module to show the sub-inch aerial photographs within the AMBIS user-interface (Figure 5-6).



a) A new map-centric interface



b) Integration of very-high resolution aerial photography

Figure 5 - 6 Modified AMBIS User Dialogs

Before a particular deployment, AMBIS imports the highway bridges to be inspected into its internal database. After this import process, a user can view these bridges on the main user interface, can query the specifications of the bridge, and proceed to the data collection deployment. AMBIS collects and processes the data and produces a distress rating for each bridge. The analysis results are then imported into the IRSV system and can be accessed through the IRSV inference engine.

After some deliberation, we decided to use XML as the format for exchanging data between AMBIS and IRSV. XML was chosen because it is designed as an open protocol for data transfer, and it is flexible in nature and easy to create and consume. Once the Document Type Definition is agreed upon, both systems can easily program a module for producing and parsing the data. Appendix A contains the DTD schema description of the exchange data format along with a sample data set.

5.3. STUDY RESULTS

The results for the deck distress portion of the analysis (DDI) are presented in Table 5-5. Although twenty-one (21) bridges were analyzed, results for only nineteen (19) were produced. Five bridges had insufficient information for a complete assessment.

In addition to the coordinates of each bridge, the table also provides information on the owner of the bridge, the main structural system associated with the construction of the bridge, the year built, the present condition (as determined by the owner of the bridge through earlier studies) and the final AMBIS rating. As discussed earlier, the final AMBIS rating represents an average of a number of different grids that make up the sample for that bridge.

Several preliminary observations can be made. Based on the ratings produced by AMPIS, there appears to be a correlation (albeit weak) between DDI rating and age of structure, i.e., the better performing bridges (from the standpoint of deck distress) appear to correspond to the newer structures – See Figure 5-6. Although there is a wide variation in the data, the trend for a positive correlation between AMBIS DDI rating and year built appears to be statistically significant.

Table 5-5 Study Results on Deck Distress

Bridge No.	GPS Longitude	GPS Latitude	Owner	Structure Type	Yr. Built	Present Condition	DDI Rating
590038	-80.86553	35.22442	NCDOT	Steel	1945	Fair	56
590049	-80.88522	35.07933	NCDOT	Concrete	1926	Fair	78
590059	-80.68953	35.25128	NCDOT	Steel	1976	Fair	-
590084	-80.73167	35.32222	NCDOT	Pre-stressed Concrete	2004	Good	98
590108	-80.83742	35.23742	NCDOT	Steel	2005	Good	85
590140	-80.55408	35.00297	NCDOT	Concrete	1951	Fair	99
590147	-80.55408	35.00297	NCDOT	Concrete	1938	Fair	99
590161	-80.00214	35.14586	NCDOT	Steel	1961	Fair	57
590165	-80.93056	35.16314	NCDOT	Steel	1975	Poor	88
590176	-80.85128	35.41492	NCDOT	Steel	1955	Fair	99
590177	-80.66333	35.25914	NCDOT	Steel	1970	Fair	66
590179	-80.78736	35.24686	NCDOT	Concrete	1937	Fair	46
590239	-80.78806	35.24694	NCDOT	Steel	1966	Fair	87
590255	-80.81336	35.24621	CDOT	Steel	1969	Fair	97
590298	-80.75361	35.32194	NCDOT	Pre-stressed Concrete	1967	Fair	-
590376	-80.88300	35.20783	CDOT	Steel	1960	Fair	66
590379	-80.86883	35.24733	CDOT	Pre-stressed Concrete	1965	Fair	85
590511	-80.74336	35.29578	NCDOT	Steel	1987	Good	83
590512	-80.74336	35.29578	NCDOT	Steel	1987	Good	83

Also, there appears to be a rough correlation between the ‘present condition’ noted by the two DOTs and the AMBIS rating, at least for the two conditions for which at least two comparisons could be made. That is, for the ‘fair’ category, the average AMBIS rating is 79, and for the ‘good’ category, the average AMBIS rating is 87. These comparisons, however, need to be viewed with caution since not a lot of data were used in making these comparisons. In addition, it is not clear what factors were considered in the condition assessments completed by the two DOTs. In Phase II, we hope to expand on these comparisons by including more bridges in different parts of the country in order to understand the robustness of these findings.

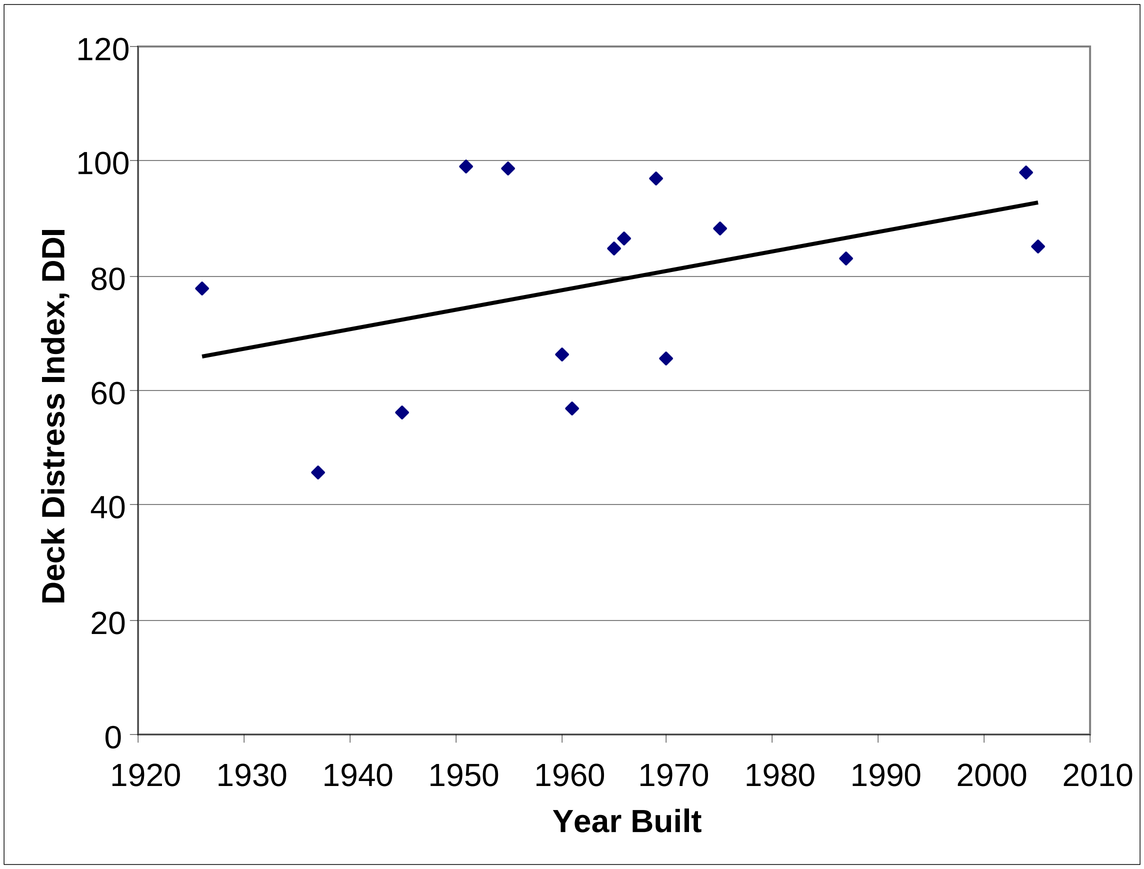
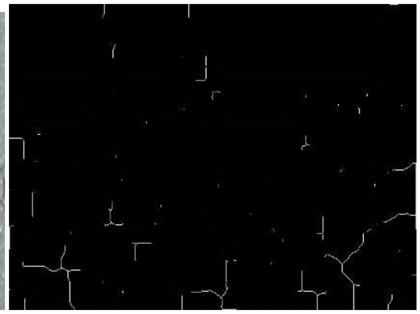
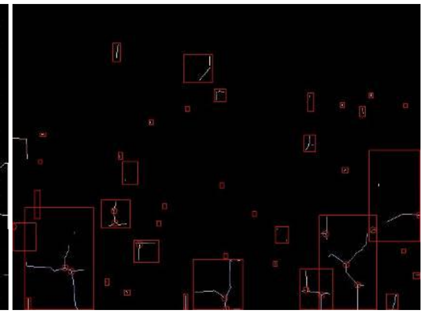
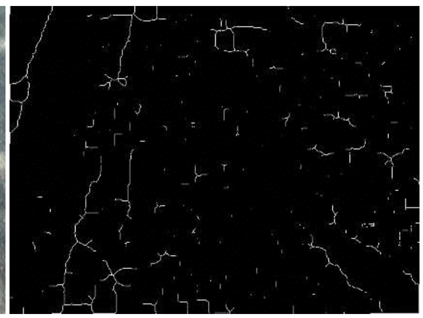
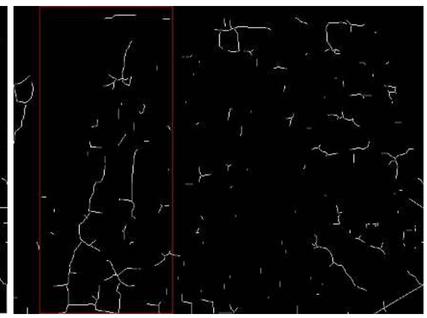
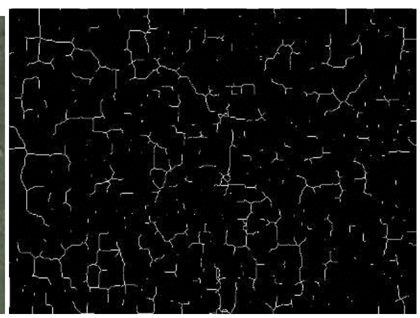
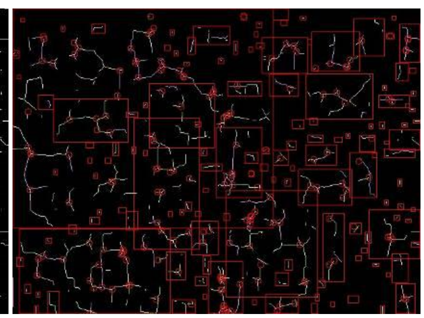
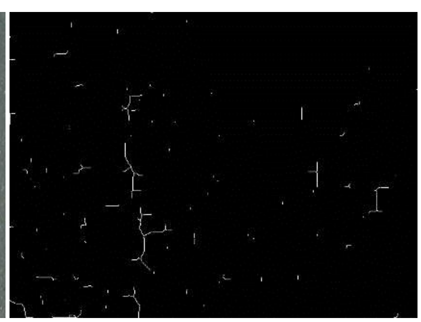
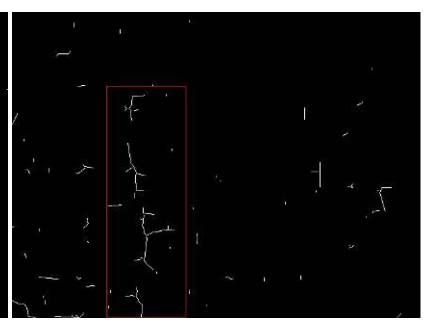


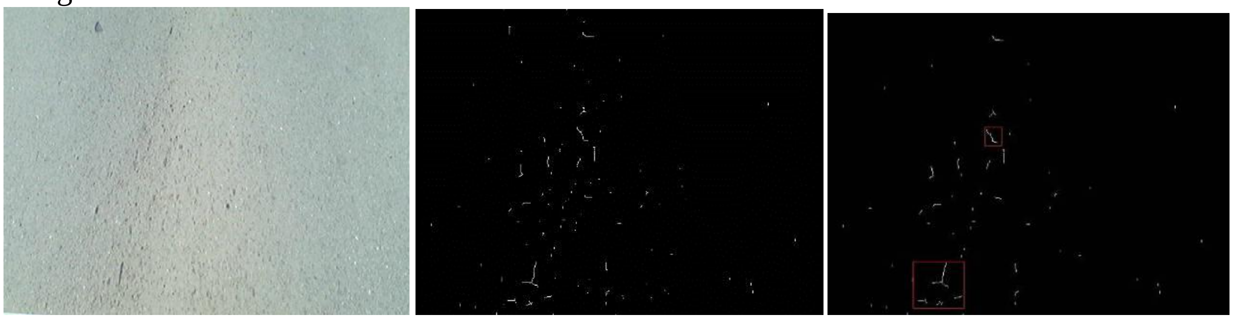
Figure 5-7 Comparison of DDI Value with Year Built

Table 5-6 shows some sample images from six different bridges. The first image (left-most image) is the raw image from the AMBIS data collection module. The second image (middle image) is the processed image representing the results of 'thinning.' The third image (right-most image) represents the results of the vectorization. It is this last image that is used in classifying the final DDI state.

Table 5-6 Samples of Thinning and Vectorization Results

RAW Image	Thinning	Vectorization
Bridge 590140		
		
Bridge 590038		
		
Bridge 590379		
		
Bridge 590165		
		

Bridge 590255



Bridge 590108

Table 5-7 shows the results from the joint separation calculation. The calculation is based on the assumption that one (1) pixel measures approximately a half inch, and the allowable joint separation is about 1.5 inches. Both of these assumptions could change if different bridge types are considered or if the resolution of the images varies more than the 0.5 inches. In Phase II, we will investigate the variation of these parameters once a larger set of bridges around the country are selected.

Table 5-7 Joint Separation Measurements using AMBIS

Bridge No.	No. of Joints	Separation (S) (no. of pixels)[1]	Avg. S[2] (in)	Max. S (in)	Comments
590038	0	-	-	-	No joints detected because of shadows
590049	0	-	-	-	No joints detected
590084	5	1,2,1,1,1	0.6	1	
590108	6	1,2,2,1,2,1	0.8	1	
590140	0	-	-	-	Failed to detect joint because of shadows
590161	3	1,1,3	0.8	1.5	Failed to detect top joint
590165	2	2,1	-	-	
590176	2	1,1	0.5	0.5	-
590177	0	-	-	-	No joints detected
590179	3	2,4,8	2.3	4	Joint obscured by joint filler
590239	2	1,1	-	-	Top joint not captured
590255	12	1,2,2,2,1,2,2,2,1,1,1,3	0.8	1.5	
590298	5	1,5,7,4,3	2	3.5	Joint separation estimate affected by shadows on right side
590376	0	-	-	-	Detection algorithm affected by side shadow
590379	3	4,2,1	1.2	2	Failed to detect middle joint
590511	7	1,3,2,1,2,3,1	0.6	1.5	
590512	7	2,2,2,4,2,2,1	0.7	2	

Note: 1: each number represents a separate joint separation measurement; 2: joint measurements based on 1 pixel equaling 0.5 inches.

Table 5-7 shows the rating assigned to each bridge based on the criteria provided in Table 5-3. Two measures of joint separation were considered in this rating, i.e., the average joint separation and the maximum joint separation. While it is evident that the average joint separation would represent the most logical value to use in the rating, we provide the output using the maximum for general context.

When the maximum AMBIS joint separation ratings are compared to the 'present condition' assignments prepared by NC DOT and CDOT, there appears to be a loose correlation between the two sets of ratings. It is clear, however, that some adjustment to the AMBIS rating criteria is needed. However, with such few data, it seems more appropriate to conduct a more thorough evaluation of the criteria presented in Table 5-3 once more bridges are entered into the analysis. For now, Table 5-8 and Table 5-9 are provided mainly as a guide to how the output from AMBIS might be used to measure the distress state of bridges based on joint separations.

Table 5-8 AMBIS Ratings for Joint Separation

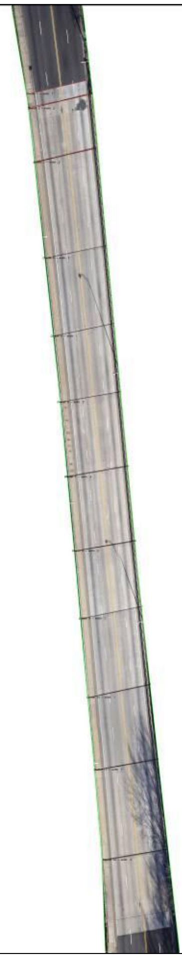
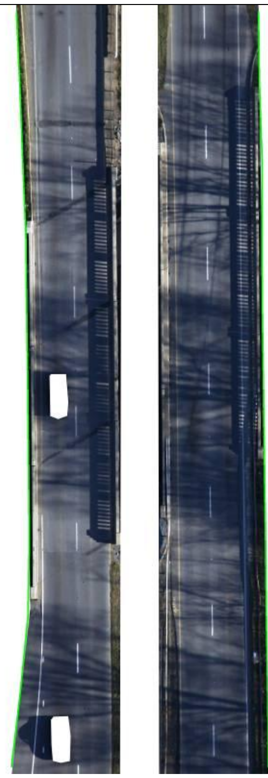
Bridge No.	Average S		Maximum S		NCDOT/CDOT Present Condition
	S, in	AMBIS Rating	S, in	AMBIS Rating	
590038	-	-	-	-	-
590049	-	-	-	-	Fair
590084	0.6	Excellent	1	Good	Good
590108	0.8	Excellent	1	Good	Good
590140	-	-	-	-	Fair
590161	0.8	Excellent	1.5	Good	Fair
590165	0.8	Excellent	1	Good	Poor
590176	0.5	Excellent	0.5	Excellent	Fair
590177	-	-	-	-	Fair
590179	2.3	Average	4	Poor	Fair
590239	0.5	Excellent	0.5	Excellent	Fair
590255	0.8	Excellent	1.5	Good	Fair
590298	2	Average	3.5	Poor	Fair
590376	-	-	-	-	-
590379	1.2	Good	2	Average	Fair
590511	0.6	Excellent	1.5	Good	Good
590512	0.7	Excellent	2	Average	Good

Table 5-9 Preliminary Comparison of AMBIS Joint Separation Ratings (Maximum S) with NCDOT and CDOT 'Present Condition' Assignments

Present Condition (NCDOT & CDOT)	AMBIS Rating based on Table 5.3 (Average S)				
		Excellent	Good	Average	Poor
	Poor	-	1	-	-
	Fair	2	2	1	2
	Good	-	3	1	-

Finally, Table 5-10 shows some sample images for four of the bridges analyzed in this study. Noted on each image in red are the delineations of the different joints. Also, noted are some of the problems that were encountered in the analysis of joint separations.

Table 5-10 Aerial Imagery Analysis – Identification of Joints

Bridge 590161	Bridge 590255	Bridges 590140-147	Bridge 590179
			
Most joints detected correctly, failed to detect top joint	Joints detected correctly	Too much shadow hindered the joint detection algorithm	Joints detected correctly

5.4. CONCLUSIONS AND RECOMMENDATIONS

5.4.1 Limitations of the Analysis

Internally, AMBIS works with image pixels as a unit. So, in theory, its resolution is the resolution of the capturing device. However, the noise reduction and classification techniques used to improve the contrast of the image may actually lead to lower resolution because of the filtering and smoothing that takes place.

During the noise reduction process, single pixels are always considered to be noise and are eliminated altogether. Also, very fine cracks may disappear after the smoothing algorithm is applied. From our experience in processing the bridge deck data for this study, after filtering and smoothing is applied, any distress feature that is less than 2-3 pixels wide and/or less than 5-8 pixels long will not likely survive the filtering process. For ground-based images, an image usually covers the width of a driving lane which is 10-12 feet (120-144 inches). The width of the image captured by AMBIS' attached camera is 640 pixels, which makes each pixel close to ¼ of an inch. So if a crack is less than ½ inch width and 4-5 inch long, it will probably be filtered out as noise.

AMPIS was initially designed to detect significant pavement distress conditions. Many of the distress patterns that the software is able to recognize are features that fill the entire image or at least a large part of the image. Micro-crack detection was not a priority and therefore the crack detection algorithms were not optimized for identifying small cracks. In Phase II, we may reassess this limitation and incorporate algorithms that are more likely pick up smaller cracks.

The result of the automated damage detection and classification recognition process for bridge surface decks depends greatly on the raw data (digital image) imported into the system. With different cover materials, the noise level within the image of the bridge deck surface may present a different amount of noise. Failure to reduce the amount of noise present in a image will cause the damage classifier to wrongly classify the damage. The rate of false positive classifications is directly related to the amount of residual noise after the initial image processing steps. Therefore, we will investigate the optimization of the noise filters using new data collected during Phase II.

The image processing algorithm still needs refinement to produce more accurate results. There are many problems that the system is still not able to resolve. Sometimes, inspectors would need to modify the classification results manually through the user-interface. While these problems are not considered major, they should be evaluated in Phase II.

For the assessment of aerial photos (i.e., measuring joint separations), the image analysis is still in the research stage. More work is needed in order to improve the damage rating resulting from an analysis of joint separation.

5.4.2 Recommendations

Remote sensing data analysis of very high-resolution aerial photographs presents some unique challenges because of the amount of data that needs to be analyzed. Although the large amount of data makes it possible to detect smaller features such as joints between bridge slabs, the high-resolution imagery also presents greater filtering challenges, as every shadow and obstacle is perfectly captured. A future research objective is to determine the optimum approach for extracting features and filter noise from these high-resolution images.

In addition to optimizing the image analysis algorithm, we must understand the significance of the metrics produced by the analysis. For example, we must addresses questions such as - if the joint has a separation of 5 inches, what type of sub-structure problems might this indicate? We are continuing to work with the entire group to interpret the results of the analysis in a manner that presents meaningful results to the bridge inspectors.

5.5. REFERENCES

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Appendix A: List of Acronyms and Definitions

AASHTO - American Association of State Highway Transportation Officials

ACI - American Concrete Institute

AMBIS – Assisted Management Bridge Information System

BHI – Bridge Health Index

BHM – Bridge Health Monitoring

BMS - Bridge Management System (more accurately called a process)

CDOT – City of Charlotte Department of Transportation

CR – Condition Rating

CRS – Commercial Remote Sensing

CRS-SI – Commercial Remote Sensing and Spatial Information

DDI – Deck Distress Index

DLF - Dynamic Load Factor

FEM - Finite Element Method

FHWA – Federal Highway Administration

GenOM – Generic Object Model

GPS - Geographical Positioning Satellite

IDE – Integrated Development Environment

ImageCat – a private sector partner in the IRSV Project

IRSV – Integrated Remote Sensing and Visualization

LiBE – LiDAR Bridge Evaluation

LiDAR – Light Distancing And Ranging

LOS – Level of Service

MR&R – Maintenance, Repair and Rehabilitation

MSVE – Microsoft Virtual Earth

NBIS – National Bridge Inspection System

NCDOT – North Carolina Department of Transportation

NCRS-T - National Consortium for Remote Sensing in Transportation

NCSBEDC – North Carolina Small Business and Economic Development Center

NDE - Non-Destructive Evaluation

NDT – Non-Destructive Testing

NEVC – Nondestructive Evaluation Validation Center

NHS – National Highway System

NIST – National Institute for Standards and Technology

OAM – Office of Asset Management, FHWA

Ontology - Another word meaning Database

PCView – Parallel Coordinate View

PDO – Problem Domain Ontology

PMS – Pavement Management System

Point Cloud – A display of 3-D surface points in a laser scanned image

PONTIS – A “Bridgeware” software suite of programs developed through AASHTO that is used by many states as part of their Bridge Management System

RITA – Research and Innovative Transportation Administration

SD/FO – Structurally Deficient and/or Functionally Obsolete

SDOF - Single-Degree-Of-Freedom

SFAP - Small Format Aerial Photography

SHM - Structural Health Monitoring

SIS – Software and Information Systems Department at UNC Charlotte

SMO – Semantic Matching Operation

SOA – Service Oriented Architecture

SPView – Scatter Plot View

SQL - Standard Query Language

UNCC – University of North Carolina at Charlotte

USDOT – United States Department of Transportation

VIS – Visualization

VisCenter – Charlotte Visualization center

Appendix B: XML Schema for IRSV Integration


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<?xml version="1.0" encoding="utf-16"?>
<xsd:schema attributeFormDefault="unqualified" elementFormDefault="qualified"
version="1.0" xmlns:xsd="http://www.w3.org/2001/XMLSchema">
  <xsd:element name="xml" type="xmlType" />
  <xsd:complexType name="xmlType">
    <xsd:sequence>
      <xsd:element name="bridge" type="bridgeType" />
    </xsd:sequence>
  </xsd:complexType>
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    <xsd:sequence>
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  </xsd:complexType>
  <xsd:complexType name="imagesType">
    <xsd:sequence>
      <xsd:element maxOccurs="unbounded" name="image" type="imageType" />
    </xsd:sequence>
  </xsd:complexType>
  <xsd:complexType name="imageType">
    <xsd:sequence>
      <xsd:element name="ID" type="xsd:int" />
      <xsd:element name="latitude" type="xsd:decimal" />
      <xsd:element name="longitude" type="xsd:decimal" />
      <xsd:element name="path" type="xsd:string" />
      <xsd:element name="date" type="xsd:dateTime" />
      <xsd:element name="distress" type="xsd:string" />
      <xsd:element name="density" type="xsd:int" />
      <xsd:element name="severity" type="xsd:string" />
      <xsd:element name="deduction" type="xsd:int" />
    </xsd:sequence>
  </xsd:complexType>
  <xsd:complexType name="infoType">
    <xsd:sequence>
      <xsd:element name="bridgeID" type="xsd:int" />
      <xsd:element name="totalSamples" type="xsd:int" />
      <xsd:element name="rating" type="xsd:decimal" />
    </xsd:sequence>
  </xsd:complexType>
</xsd:schema>
```

The following is a sample of an XML data exchange file that was produced by AMBIS and imported into IRSV


```
<xml>
   <bridge>
      <info>
         <bridgeID>590176</bridgeID>
         <totalSamples>176</totalSamples>
         <rating>98.6988636363636</rating>
      </info>
      <images>
         <image>
            <ID>6416</ID>
            <latitude>35.3979066666667</latitude>
            <longitude>-80.8510766666667</longitude>
            <path>CAP000001.bmp</path>
            <date>6/1/2009 9:06:01 AM</date>
            <distress>N/A</distress>
            <density>0</density>
            <severity>N/A</severity>
            <deduction>0</deduction>
         </image>
         <image>
            <ID>6417</ID>
            <latitude>35.3979175925926</latitude>
            <longitude>-80.8510801851852</longitude>
            <path>CAP000002.bmp</path>
            <date>6/1/2009 9:06:01 AM</date>
            <distress>N/A</distress>
            <density>3</density>
            <severity>N/A</severity>
            <deduction>0</deduction>
         </image>
            <ID>6591</ID>
            <latitude>35.3978933333333</latitude>
            <longitude>-80.85114</longitude>
            <path>CAP000176.bmp</path>
            <date>6/1/2009 9:07:41 AM</date>
            <distress>N/A</distress>
            <density>0</density>
            <severity>N/A</severity>
            <deduction>0</deduction>
      </images>
   </bridge>
</xml>
```

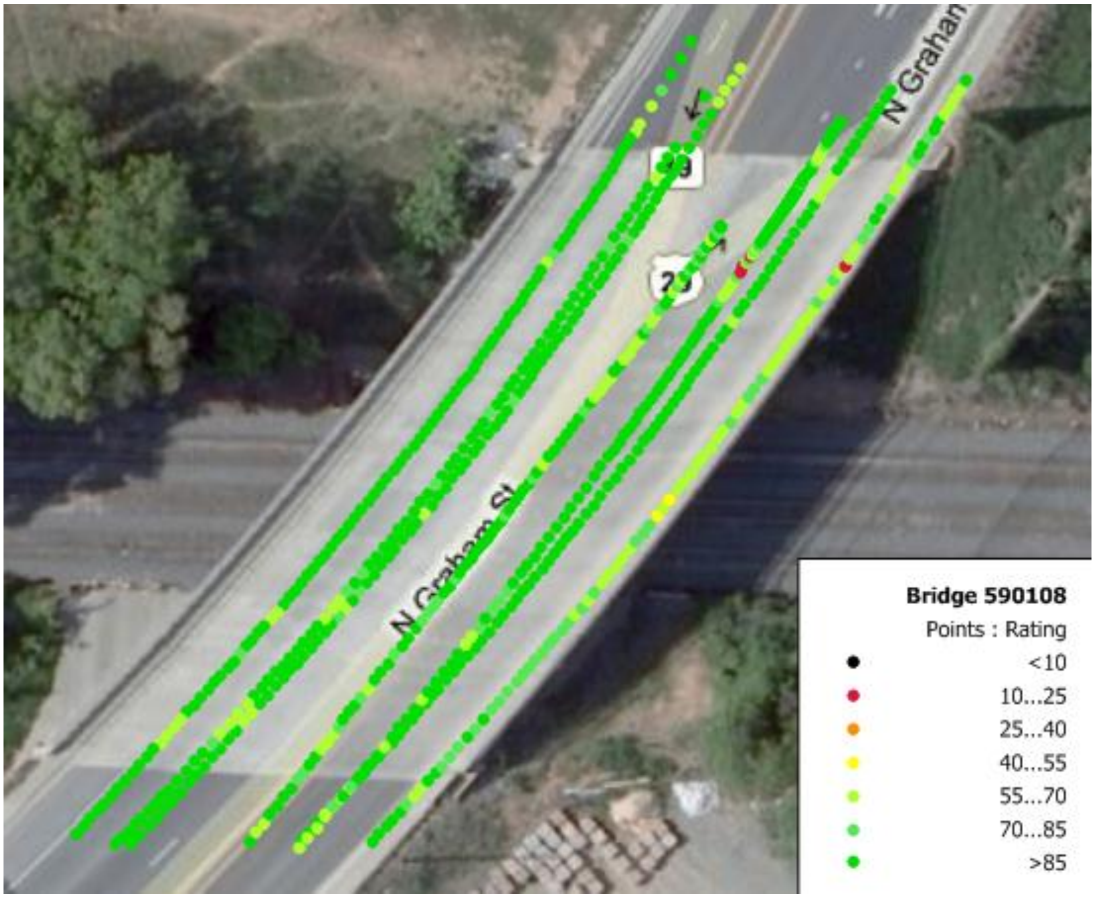
Appendix C: AMBIS Ratings for Bridge Deck Distress

Bridge 590038
Total Samples: 238
AMBIS Rating: 56.33

Bridge 590049
Total Samples: 200
AMBIS Rating: 77.62

Bridge 590084
Total Samples: 540
AMBIS Rating: 98.16

Bridge 590108
Total Samples: 734
AMBIS Rating: 85.07



Bridge 590140/590147
Total Samples: 50
AMBIS Rating: 99.1

Bridge 590161
Total Samples: 273
AMBIS Rating: 56.88

Bridge 590165
Total Samples: 168
AMBIS Rating: 88.11

Bridge 590176
Total Samples: 164
AMBIS Rating: 98.69

Bridge 590177
Total Samples: 171
AMBIS Rating: 65.62

Bridge 590179
Total Samples: 470
AMBIS Rating: 45.7

Bridge 590239
Total Samples: 508
AMBIS Rating: 86.65

Bridge 590255
Total Samples: 1091
AMBIS Rating: 96.9

Bridge 590376
Total Samples: 207
AMBIS Rating: 66.18

Bridge 590379
Total Samples: 40
AMBIS Rating: 84.83

Bridge 590511/590512
Total Samples: 303
AMBIS Rating: 82.85