Final Report

RI98-001

Bridge Deck Condition Studies in Missouri

Utilizing Ground Penetrating Radar

MISSOURI DEPARTMENT OF TRANSPORTATION
RESEARCH, DEVELOPMENT AND TECHNOLOGY

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JEFFERSON CITY, MISSOURI
DATE: September 2001

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. RDT01-012	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Bridge Deck Condition Studies in Missouri Utilizing Ground Penetrating Radar**		5. Report Date September 4, 2001 6. Performing Organization Code
7. Author(s) Steve Cardimona, Brent Willeford, John Wenzlick, Neil Anderson		8. Performing Organization Report No. RI98-001
9. Performing Organization Name and Address University of Missouri – Rolla Department of Geology and Geophysics, B-43 McNutt Hall 1870 Miner Circle, Rolla, MO 65409-0410		10. Work Unit No. 11. Contract or Grant No.
12. Sponsoring Agency Name and Address Missouri Department of Transportation Research, Development and Technology P. O. Box 270-Jefferson City, MO 65102		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes The investigation was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.		

16. Abstract

Ground penetrating radar (GPR) surveys have been performed over the driving lane of eleven bridges and deterioration analysis results were compared with what ground truth was available. Results of this work suggest that GPR will yield good estimates of chain drag hollow areas, debonding, half-cell potential, and rebar corrosion. This study demonstrates GPR is effective by yielding deterioration estimates for key bridges in Missouri, and delineates interpretation methodologies appropriate for the current state-of-the-practice in high-resolution GPR imaging. It was determined high frequency ground coupled radar, keying off the reflection amplitude and signal travel time from the top rebar mat, may more accurately define deterioration in reinforced concrete bridge decks but more study is needed on characterization of different types of deterioration and more work on making data acquisition less disruptive to traffic. GPR would be a good screening tool for MoDOT to reduce the amount of present manual in-depth deck surveys done before bridge rehabilitation projects.

17. Key Words Ground Penetrating Radar, concrete, bridge, deck, delamination, deterioration		18. Distribution Statement No restrictions. This document is available to the public through National Technical Information Center, Springfield, Virginia 22161	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 22	22. Price

Form DOT F 1700.7 (06/98)

EXECUTIVE SUMMARY

Ground penetrating radar (GPR) surveys were performed over the driving lanes of eleven Missouri bridges, and deterioration analysis results were compared with what ground truth was available. The bulk of the work was completed utilizing a new antenna designed for bridge deck evaluation, although comparison took place of the results on one bridge using this new antenna and older antennae. The good correlation obtained with the ground truth shows that GPR can give percent deterioration estimates that are accurate. The determination of the type of deterioration (delamination, debonding) using GPR alone is difficult and requires ground truth for calibration and pattern recognition. Results of this work suggest that GPR will yield good estimates of chain drag hollow areas, debonding, half-cell potential, and rebar corrosion. This study demonstrates GPR is effective by yielding deterioration estimates for key bridges in Missouri and delineates interpretation methodologies appropriate for the current state-of-the-practice in high-resolution GPR imaging. It was determined high frequency ground coupled radar, keying off the reflection amplitude and signal travel time from the top rebar mat, may more accurately define deterioration in reinforced concrete bridge decks, but more study is needed on characterization of different types of deterioration and more work on making data acquisition less disruptive to traffic. GPR would be a good screening tool for MoDOT to reduce the amount of present manual in-depth deck surveys done before bridge rehabilitation projects.

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INTRODUCTION

Ground penetrating radar (Daniels, 1996; Cardimona, et al., 1998) uses a radio wave source to transmit a pulse of electromagnetic energy into a nonmagnetic body. The reflected energy, originating within the body at interfaces between materials of different dielectric properties or of differing conductivities, is received and recorded for analysis of internal structure of the body. GPR data consist of a) changes in reflection strength, b) changes in arrival time of specific reflections, c) source wavelet distortion, and d) signal attenuation. When applied to the analysis of bridge decks, these different GPR signatures may be used for detecting internal corrosion of steel reinforcement within the concrete deck, which can be an indicator of poor quality overlay bonding or delamination at the rebar level.

Ground penetrating radar instrumentation and techniques applied to bridge deck assessment offer the ability to gain information about the condition of bridge decks in a more rapid and less costly fashion than coring and perhaps will yield more reliable assessment than current geotechnical procedures (e.g., ASTM D 4580-86). Only recently has the instrumentation been improved so that interpretable high resolution data can be obtained regarding pavement and bridge condition. The instrumentation and methodologies are still in the developmental and testing stage, although there are guidelines for the interpretation of such data (e.g., AASHTO TP36-93).

Because the radar propagated in the bridge deck materials will be very sensitive to metal, diffractions from the rebar reinforcement will be clearly seen in the GPR reflection data. The strength of the radar returns (from the rebar reinforcement and internal layering) can be directly associated with the amount of deterioration; i.e., the lower the signal strength the more deck deterioration is present. In addition to amplitude information, the radar signal also has travel time

information; i.e., the later the arrival time of the return from the same depth within the concrete (e.g., the rebar mat) is indicative of an increased dielectric constant (decreased electromagnetic velocity). Automated interpretation schemes try and duplicate what visual inspection can pull out in terms of the variability in these two diagnostic indicators (amplitude and travel-time).

This study tested and compared two modern antennae designs for bridge deck assessment (Cardimona et al., 1999). The objective was to find which one would give the best data to determine deterioration in the reinforced concrete. These are the 1.0GHz air-launched horn antennae and the 1.5GHz ground-coupled antennae (antennae model #'s 4208 and 5100 developed by Geophysical Survey Systems, Inc.). Both are considered very high radar frequency (1.0-1.5 x 10^9 Hz), offering the ability to obtain high resolution images of pavement layers. The 1.0GHz bistatic horn antennae, normally mounted behind a truck, were initially designed for high speed road pavement imaging. The 1.5 GHz ground-coupled antennae are quite new and were designed specifically for bridge-deck assessment. The higher peak frequency, and being ground-coupled instead of air-launched, allows these antennae to give an unprecedented image of the upper rebar mat within a bridge deck (Cardimona et al., 1999). The technique for collecting data with the ground-coupled antennae necessitates slower acquisition than with the air-launched antennae; however, positioning of the survey lines is exact, and the increased detail offered by the instrument can be important for interpretation and deterioration assessment. Still, acquisition is relatively rapid and a bridge can be surveyed in a very short time.

TECHNICAL APPROACH

Starting in the summer of 1998 and continuing in winter/spring 1999, the Department of Geology and Geophysics at the University of Missouri-Rolla collected GPR data over the driving lane of eleven key bridges in Missouri. The instruments and the software for analysis of the data are manufactured by Geophysical Survey Systems, Inc. Table 1 summarizes the specs on the bridges. Available ground truth consisted of one or more of the following: chloride sample points, half-cell potentials, core information and MoDOT field map showing patches and cracking from visual assessment and debonding from chain drag testing (Table 1).

Table 1

Bridge No	Hwy	Direction	City	Survey Length	Ground Truth
A9012	I70 N Outer Rd	East	St.Charles	125ft	FM
A2684	141	North	Arnold	105ft	FM,CL,HC
A2684	141	South	Arnold	100ft	FM,CL,HC
A2683	141	North	Arnold	150ft	FM,CL,HC,CR
A2683	141	South	Arnold	150ft	FM,CL,HC
A2682	141	South	Arnold	100ft	FM,CL,HC
A2682	141	North	Arnold	100ft	FM,CL,HC,CR
A2109	54	South	Kingdom City	215ft	FM,CL
H284	54	North	Kingdom City	215ft	FM
L964R	54	North	Kingdom City	215ft	FM
L964R	54	South	Kingdom City	215ft	FM

FM = Field map showing patches and cracks (visual inspection) and debonding (chain drag)
Cl = Chloride ion concentration
HC = Half-Cell potentials
CR = Core information

On each bridge the 1.5GHz ground-coupled antennae was used. For the St. Charles bridge (Table 1), data was also acquired using the air-launched horn antennae for comparison (Cardimona et al., 1999). Table 2 summarizes our acquisition parameters and survey design for each case. Except for St. Charles, all survey lines were offset 1ft for a total transverse coverage of 10ft across the bridge lane (11 survey lines down the length of each lane in the bridge). Acquisition in scans/meter varied (Table 2), but a constant 10ns total time window of recording was used in all cases. The lower the scan rate, the faster the acquisition could be performed. After testing three different rates, we determined that 60 scans/meter was optimum for acquisition with the ground-coupled 1.5 GHz antennae.

Table 2

Bridges	Scan Rate	Recording time	Number of survey lines
Arnold	60 scans/m	10ns	11 lines @ 1ft offset
Kingdom City	40 scans/m	10ns	11 lines @ 1ft offset
St. Charles	80scans/m (1.5GHz)	10ns	5 lines @ 2ft offset
	20 scans/m (1.0GHz)	10ns	6 lines @ 2ft offset

Except for the St. Charles bridge (Cardimona et al., 1999) the interpretation steps were the same for all the 1.5GHz radar data. Processing and analysis of the data included:

1) creation of a 3-D data file (including appropriate line offset for the multiple-line surveys),
2) visual pick of areas with anomalous signal (increased travel times and/or lower amplitudes), color coding areas as white or black (i.e., good or bad),
3) pick rebar reinforcement amplitude and travel times (top rebar mat) and save info to file for contour plotting,
4) compare with ground truth after scanning in deck maps provided by MoDOT and including all available ground truth information.

For the St. Charles bridge, additional processing of the air-launched horn antennae data was performed for comparison with the rebar amplitude picks from the 1.5GHz ground coupled antennae data. This processing involved subtracting the returned signals from antennae oriented in two perpendicular directions to enhance the ability to pick the top rebar amplitudes (Cardimona et al., 1999).

Figure 1 shows example data, displaying radar reflection profiles across areas where the radar signal is clearly interpretable. Where the amplitude and travel time (depth) of the radar returns are laterally continuous, the bridge is determined to be in good condition. Where there are amplitude and phase (travel time) variations, areas of possible deterioration can be mapped. Figure 2 shows an example where interpretation is more difficult due possibly to design/construction variation.

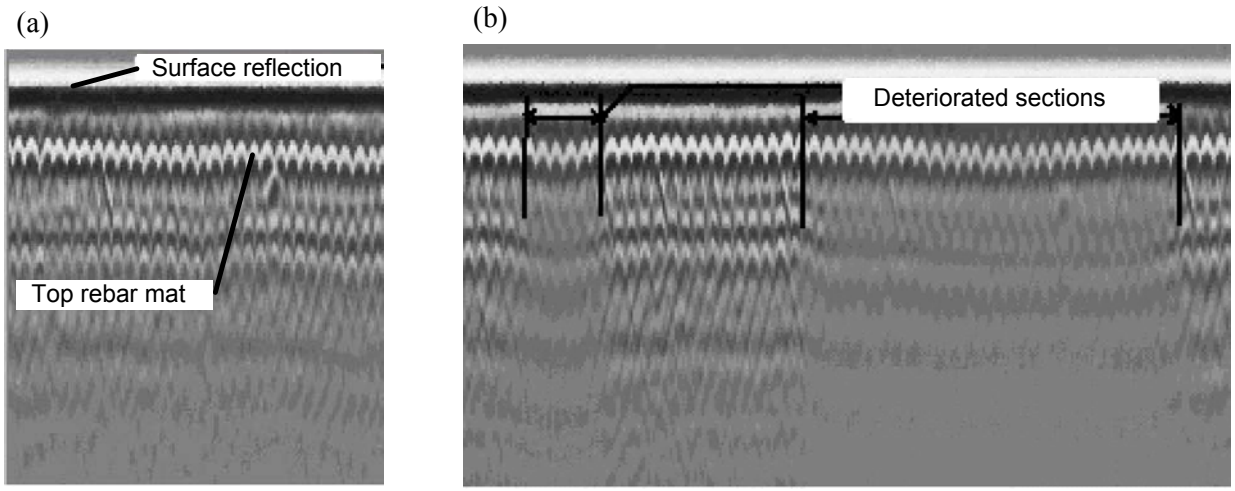

Figure 1. Example from St Charles bridge (#A9012): (a) consistent signature from the top-rebar mat; (b) signature displaying amplitude and travel-time anomalies distinguishing areas of possible deterioration.

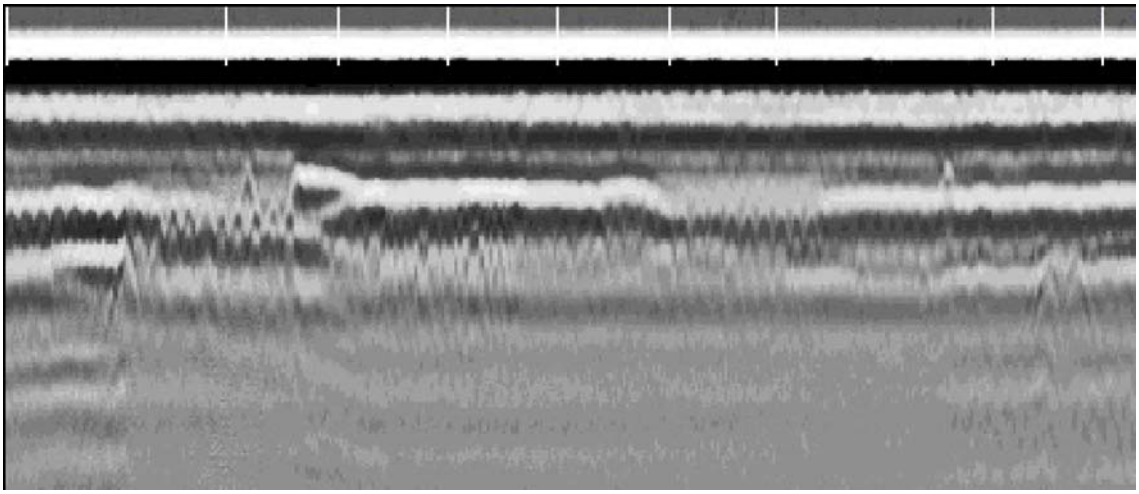

Figure 2. Example bridge L964R North, Kingdom City, MO. Lateral amplitude and phase variations, perhaps due to design and construction, make interpretation more challenging in terms of possible deteriorated sections.

The degradation of the radar signal shows up as a loss in amplitude of the rebar reflection and an increase in travel time to the rebar layer. Both of these changes in signature are indications that the rebar is deteriorated and the region above the rebar is compromised in some fashion. Although no imaging of debonding or delamination is measured directly, the radar reflection character is related directly to the amount of debonding/delamination, which allows (chloride-bearing) fluids to reach the rebar mat. After detailed visual assessment and/or amplitude mapping, a contour plot of each bridge deck showing good and bad areas is produced. Where visual assessment was not possible (Figure 2), only variation in the radar reflection amplitude from the top rebar mat is used as an indicator of possible deterioration. Using strictly a visual assessment, a black and white result (i.e., it is either bad or good) is determined automatically. Using the character of the top rebar mat, the result is a contour plot of amplitude or two-way travel time (indicative of velocity variation) that is more of a continuum. These plots must be calibrated in order to determine what the cut-off values must be for determining good versus bad. Figures 3a and 3b display interpretation results for bridge #A9012 (St Charles) where rebar amplitude mapping was used.

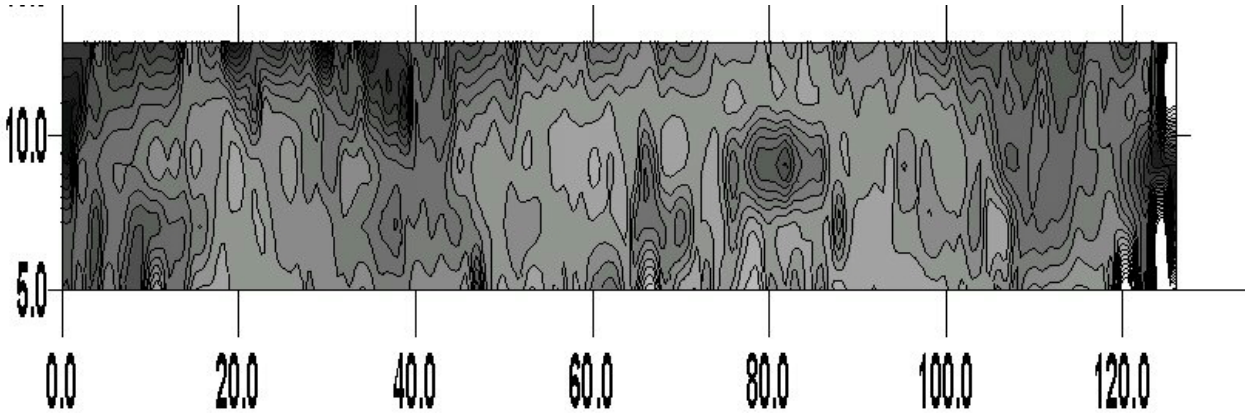

Figure 3a. Map-view of rebar reflection amplitude contoured after data analysis of bridge #A9012 (St. Charles). Dark spots are "hot", associated with loss of radar amplitude indicating that bridge integrity in those areas may be compromised.

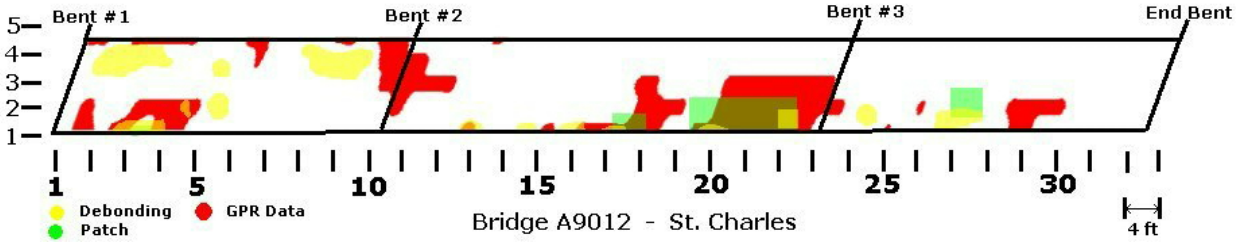

Figure 3b. Map-view of interpreted condition assessment after rebar reflection amplitude analysis of bridge #A9012 (St. Charles). Colored spots highlight surface patches as well as debonding determined by chain drag testing.

RESULTS AND DISCUSSION

Figures 4-13 show the results of analyses as well as ground truth for each of the other bridges.

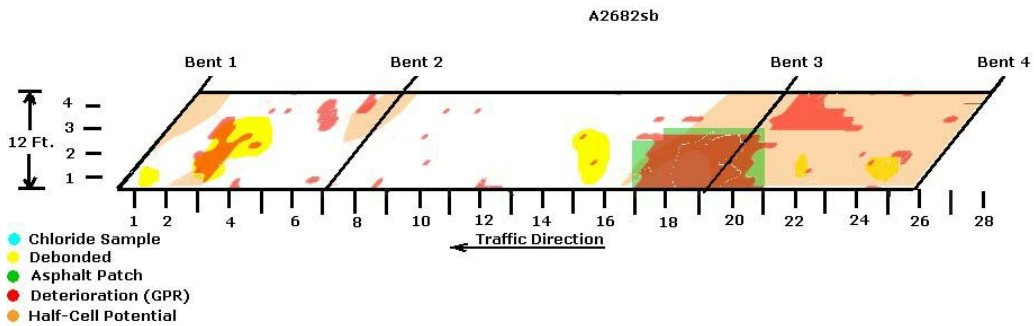

Figure 4. Map-view of interpreted condition assessment after visual analysis of radar data for bridge #A2682 southbound (Arnold). Colored spots highlight surface patches as well as debonding determined by chain drag testing. Also plotted are half-cell potential results and chloride sample locations.

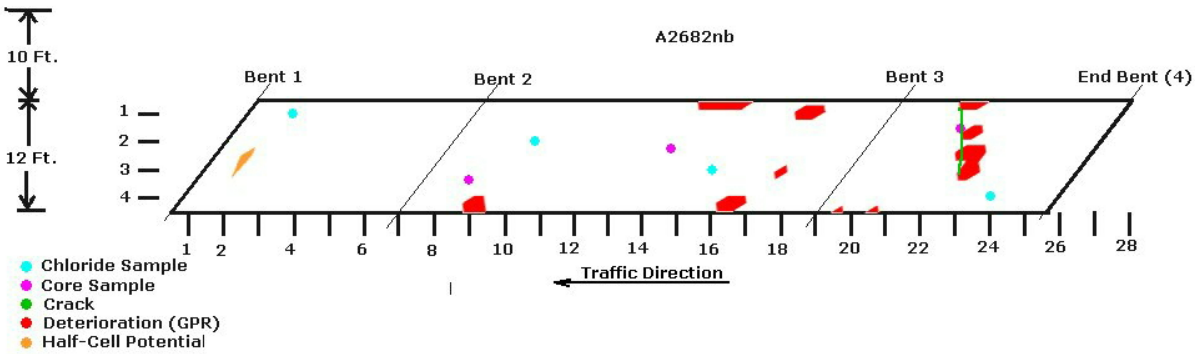

Figure 5. Map-view of interpreted condition assessment after visual analysis of radar data for bridge #A2682 northbound (Arnold). Colored areas highlight surface cracking as well as core and chloride sample locations. Also plotted are half-cell potential results.

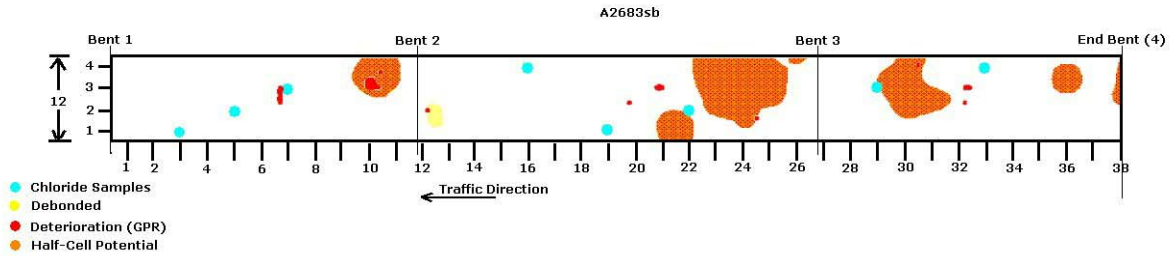

Figure 6. Map-view of interpreted condition assessment after visual analysis of radar data for #A2683 southbound (Arnold). Colored areas highlight debonding (determined by chain drag testing), half-cell potential results, and locations of chloride sampling.

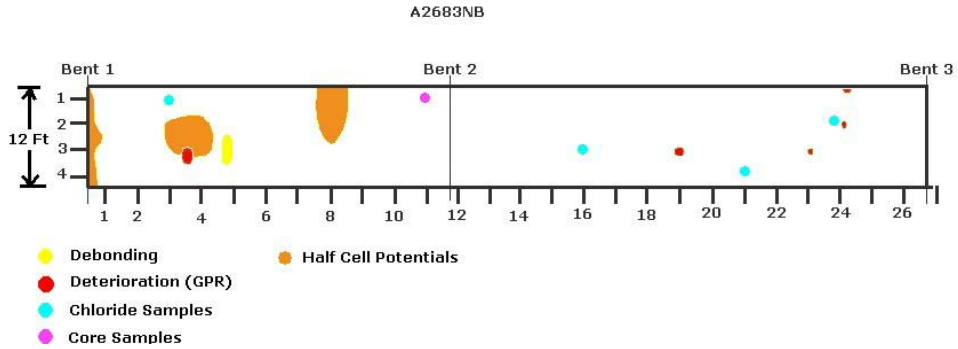

Figure 7. Map-view of interpreted condition assessment after visual analysis of radar data for #A2683 northbound (Arnold). Colored areas highlight debonding (from chain drag testing) and half-cell potential results. Also noted are core and chloride sample locations.

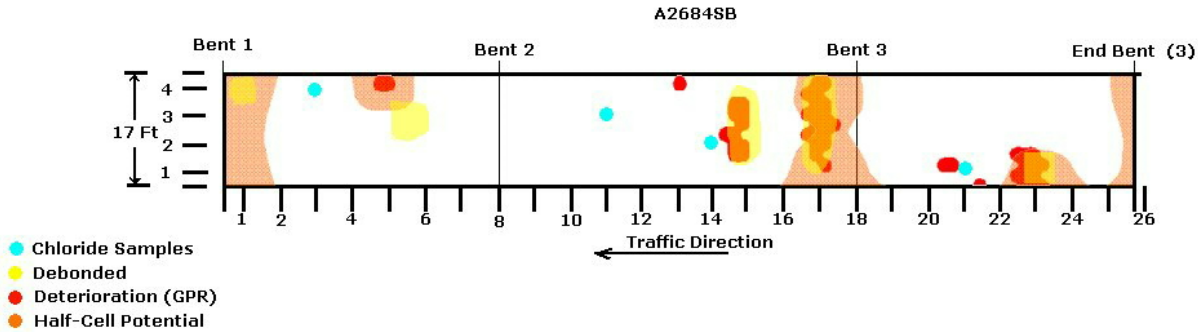

Figure 8. Map-view of interpreted condition assessment after visual analysis of radar data for #A2684 southbound (Arnold). Colored spots highlight debonding (determined by chain drag testing) and half-cell potential results. Also noted are chloride sample locations.

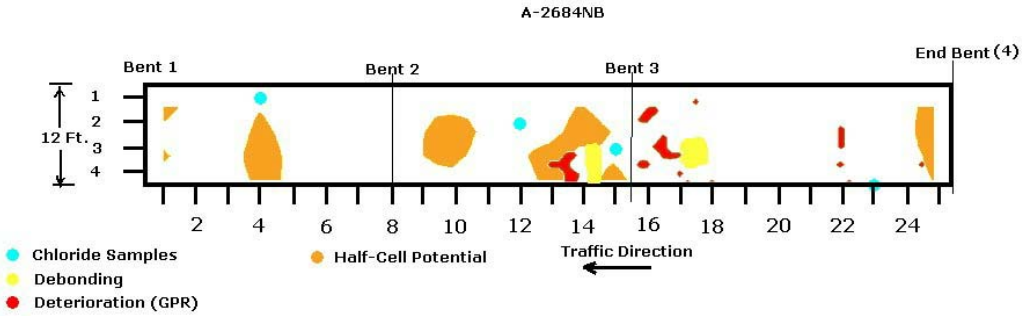

Figure 9. Map-view of interpreted condition assessment after visual analysis of radar data for #A2684 northbound (Arnold). Colored spots highlight debonding (determined by chain drag testing) and half-cell potential results. Also noted are chloride sample locations.

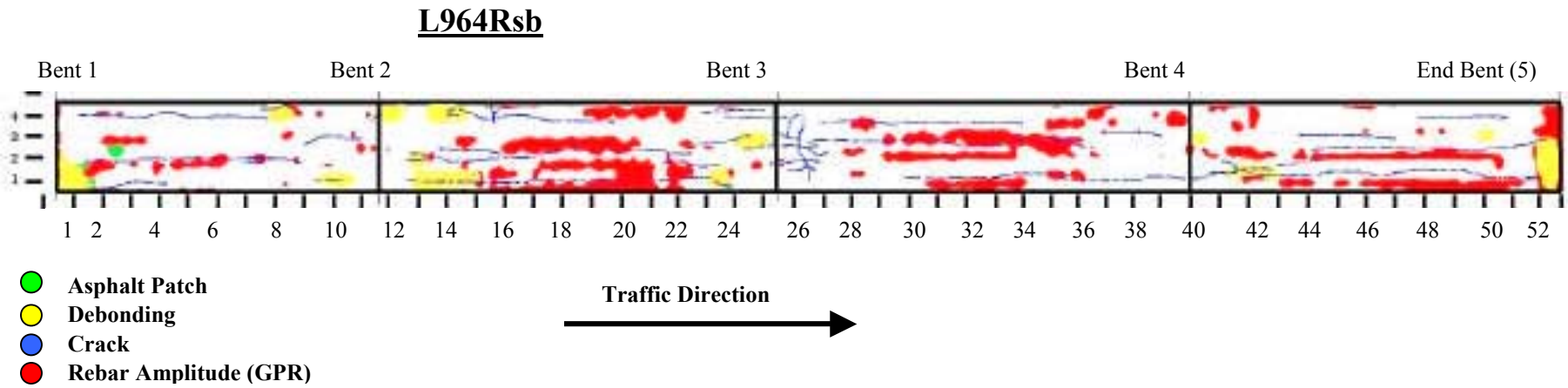

Figure 10. Map-view of interpreted condition assessment after rebar reflection amplitude analysis of bridge #L964R southbound (Kingdom City). Colored areas highlight surface patches and cracks as well as debonding as determined through chain drag testing.

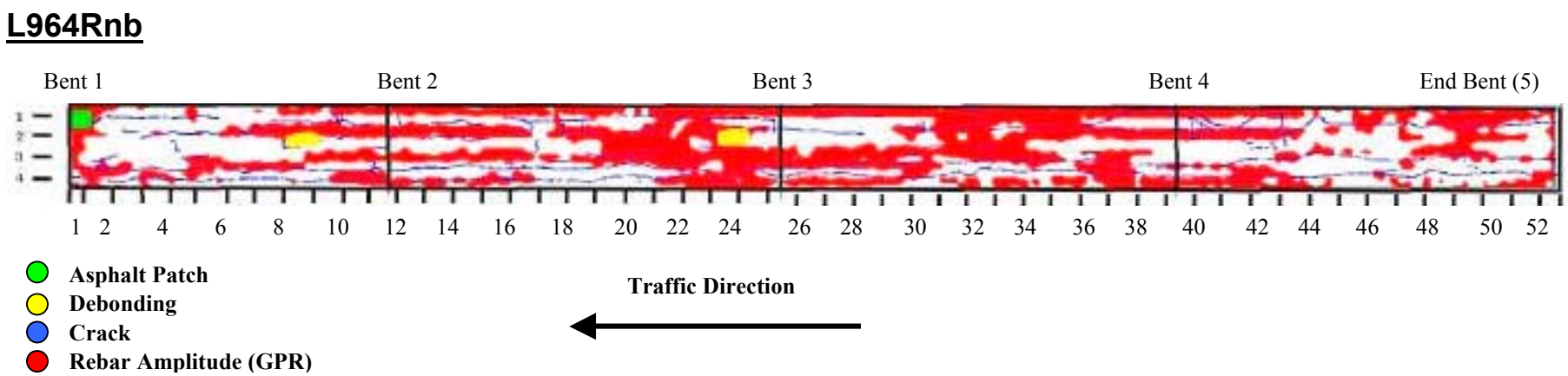

Figure 11. Map-view of interpreted condition assessment after rebar reflection amplitude analysis of bridge #L964R northbound (Kingdom City). Colored areas highlight surface patches and cracks as well as debonding as determined through chain drag testing.

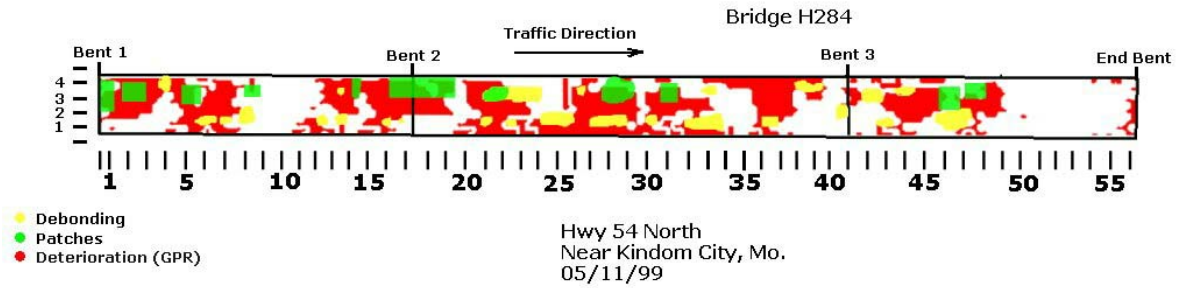

Figure 12. Map-view of interpreted condition assessment after visual analysis of radar data for bridge #H284N (Kingdom City). Colored spots highlight surface patches as well as debonding determined by chain drag testing.

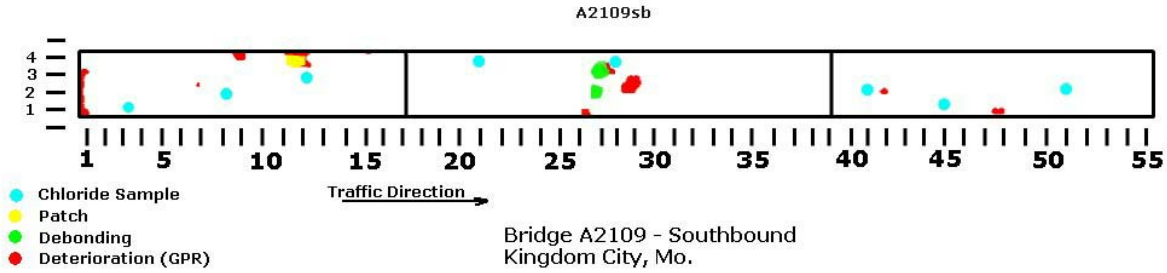

Figure 13a. Map-view of interpreted condition assessment after visual analysis of radar data for bridge #A2109 (Kingdom City). Colored areas highlight surface patches as well as debonding determined by chain drag testing. Chloride sample locations are noted.

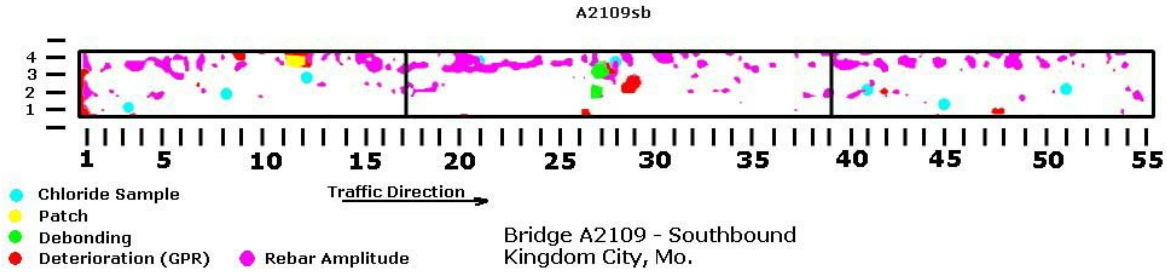

Figure 13b. Map-view of interpreted condition assessment of bridge #A2109 (Kingdom City). Colored areas highlight same features as in Figure 13a with results from rebar amplitude analysis shown as well.

CONCLUSIONS

In this report, the utility of ground penetrating radar to image subsurface structure within concrete, rebar-reinforced bridge decks has been demonstrated. Mapping the degradation of the radar signal (i.e., the loss in amplitude and/or an increase in travel time for returns from internal layering) gives an indication whether or not the rebar is deteriorated and the region above the rebar is compromised in some fashion. The radar reflection character is related directly to the amount of debonding/delamination which allows (chloride-bearing) fluids to reach the rebar. Using strictly a visual assessment of the radar scans, one can automatically come up with a result showing good and bad areas of the bridge that is in agreement with ground truth. In this study, using the high frequency ground coupled radar and keying on the reflection from the top rebar mat showed better results than the air launched system used in the past. Using the radar reflection character of the top rebar mat, a contour plot of amplitude or two-way travel time (indicative of velocity variation) that is a continuum across the bridge deck is produced. One must calibrate these contour plots in order to determine what the cut-off values must be for determining good versus bad concrete. It might be guessed that each bridge has a condition that is a continuum, from very good areas to very bad areas, and thus the black and white delineation is not as accurate. However, when trying to determine percent deterioration of a bridge, the black and white descriptor is required. The good correlation with ground truth shows that GPR can give total percent deterioration estimates that are accurate. The determination of the type of deterioration (delamination, debonding) using GPR alone is difficult and requires ground truth for calibration and pattern recognition. Results of this work suggest that GPR will yield good estimates of the total deteriorated area of bridge deck, which correlate well with ground truth data from a combination of methods using chain drag (showing hollow areas, debonding),

half-cell potentials and chloride sampling (rebar corrosion). At this time, a good use for GPR at MoDOT would be as a screening tool to determine if full scale manual deck surveys should be done.

RECOMMENDATIONS

Future work is suggested from the experience learned in this study:

1) Use (different types of) ground truth to calibrate the deterioration images based on the radar reflection amplitude from the rebar or based on radar reflection travel time. Using this calibration, transform the contoured data into a black and white map view of bad/good areas. The advantage of this would be more accurate totals of deteriorated concrete needing patching and better estimates for concrete repair quantities.

2) Compare visual inspection results with results based on radar reflection amplitude and/or travel time to see if it is more accurate than present methods. Using the rebar reflection amplitude from the ground coupled, high frequency, antenna appears promising in finding more of the deteriorated concrete than visual assessment of the data from the present typical air launched systems. Also, data collection with the ground coupled radar takes more time and is more obstructive to traffic, and investigation into methods to speed data acquisition are needed.

3) Compare results with Strategic Highway Research Program (SHRP) (or other such as Hermes) results on same bridges. Do a side by side comparison of each system, ground coupled, air launched and HERMES to evaluate the accuracy and mobility of the systems to meet MoDOT's needs.

4) Investigate ways to determine more directly what the deterioration identified by GPR data is, whether it is debonding vs. delamination. Determine not just that *there is* a problem, but *what is*

the problem; can certain characterizations be found in the GPR data for debonding, delamination and even corrosion and chloride content.

5) Consider using GPR as a screening tool, to reduce the number of bridges on the rehabilitation list from those requested to do deck inspections to those that actually need to have a full scale manual deck survey.

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