IDEA

Innovations Deserving Exploratory Analysis Programs

NCHRP IDEA Program

Vertical Electrical Impedance Scanner for Concrete Bridge Deck Assessment without Direct Rebar Attachment

Final Report for
NCHRP IDEA Project 202

Prepared by:
Brian A. Mazzeo
W. Spencer Guthrie
Brigham Young University

August 2019

TRB TRANSPORTATION RESEARCH BOARD
The National Academies of
SCIENCES · ENGINEERING · MEDICINE

Innovations Deserving Exploratory Analysis (IDEA) Programs Managed by the Transportation Research Board

This IDEA project was funded by the NCHRP IDEA Program.

The TRB currently manages the following three IDEA programs:

- The NCHRP IDEA Program, which focuses on advances in the design, construction, and maintenance of highway systems, is funded by American Association of State Highway and Transportation Officials (AASHTO) as part of the National Cooperative Highway Research Program (NCHRP).
- The Safety IDEA Program currently focuses on innovative approaches for improving railroad safety or performance. The program is currently funded by the Federal Railroad Administration (FRA). The program was previously jointly funded by the Federal Motor Carrier Safety Administration (FMCSA) and the FRA.
- The Transit IDEA Program, which supports development and testing of innovative concepts and methods for advancing transit practice, is funded by the Federal Transit Administration (FTA) as part of the Transit Cooperative Research Program (TCRP).

Management of the three IDEA programs is coordinated to promote the development and testing of innovative concepts, methods, and technologies.

For information on the IDEA programs, check the IDEA website (www.trb.org/idea). For questions, contact the IDEA programs office by telephone at (202) 334-3310.

IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

Vertical Electrical Impedance Scanner for Concrete Bridge Deck Assessment without Direct Rebar Attachment

IDEA Program Final Report

NCHRP-IDEA 202

Prepared for the IDEA Program

Transportation Research Board

The National Academies

Brian A. Mazzeo, Ph.D., Professor

W. Spencer Guthrie, Ph.D., Professor

Brigham Young University

August 31, 2019

ACKNOWLEDGEMENTS

This work was funded by the Transportation Research Board (TRB) of the National Academies under the TRB-IDEA Program (NCHRP-202). A special thanks is extended to the TRB Program Director, Inam Jawed, and the Advisory Panel, including Ivan Lasa, IDEA Advisor, Steel Material Products Administrator, Florida Department of Transportation; Hajin Choi, Assistant Professor, Soongsil University, South Korea; Dick Dunne, Director of Structural Engineering, Michael Baker International; Russell Lay, Bridge Engineer, Morrison Maierle; John Popovics, Professor of Civil Engineering, University of Illinois at Urbana-Champaign; and Jason Richins, Resident Engineer, Region 3 Construction, Utah Department of Transportation.

The researchers thank Fouad Jaber, Mike Vigil, Kent Miller, Jason Volz, Jinying Zhu, Chungwook Sim, Jeff Barton, Jared Baxter, Lorin Hendricks, Tenli Waters, Enoch Boekweg, Nick Bragg, and Mavrik Thomas for their assistance in this work. Additionally, the researchers thank the Utah Department of Transportation and the Nebraska Department of Transportation for additional support.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Chloride-induced corrosion of steel reinforcement in concrete bridge decks is a major concern for bridge owners and managers. Bridge decks in marine areas and cold regions experience rapid and widespread steel corrosion due to the presence of elevated concentrations of salts that are either naturally present in the marine environment or deliberately applied in cold regions for safety. As shown in Figure 1, over time, salts can diffuse through the concrete cover, after passing through any overlays that may be applied to the deck surface, and initiate corrosion of the steel reinforcement. Because corrosion at an early stage occurs internally where it is not visible, visual inspection alone is not adequate to evaluate the protection against chloride ingress that is offered to steel reinforcement. By the time delamination and spalling of the concrete occur, rehabilitation is costly and often involves traffic disruption to perform the necessary repairs. As indicated in a survey of transportation officials in many states, more than half of a typical bridge maintenance budget is allocated to maintenance of bridge decks [1]. Because early intervention, before concrete cracking has occurred, is the most cost-efficient bridge deck management approach, a device for measuring the quality of protection offered to the steel reinforcement on bridge decks was needed.

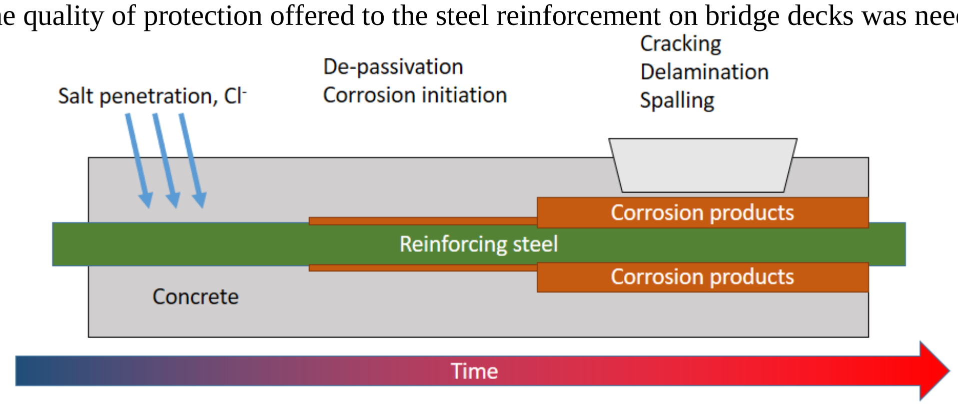


FIGURE 1 Process of deterioration for concrete bridge decks exposed to chloride-based salts.

Among the many techniques available for assessing the condition of concrete bridge decks, vertical electrical impedance (VEI) measurements have been shown to provide a quantitative measure of the protection offered to the steel reinforcement against chloride ingress. However, major limitations to using VEI in the field have been the following:

(1) The need to directly connect to the steel reinforcement to perform a VEI measurement and then to drag a wire from this direct connection to the measurement location
(2) Single-channel probes mounted to small carts that had limited data collection speed and exposed the operator to potential traffic hazards
(3) Lack of established measurement protocols and standards across different bridge deck conditions and overlay types to establish validation of the technique
(4) Lack of robust mapping techniques for presenting spatial variations in VEI measurements on a bridge deck

All four of these limitations were successfully addressed during the development of the multi-channel VEI scanner shown in Figure 2. The key to this success was the theoretical and practical development of a large-area electrode (LAE) to replace the direct tapped connection to steel reinforcement. Investigating this LAE concept in the field with support from the Utah Department of Transportation and the Nebraska Department of Transportation, extensive testing of the VEI scanner was performed on multiple concrete bridge decks, with and without overlays, that were constructed using both uncoated and epoxy-coated reinforcing steel in Utah and Nebraska in 2018. VEI scanning of full traffic lanes at rates exceeding 1500 ft^2/minute was achieved in this project.

Remarkably, the VEI scanner is able to operate in conditions where other techniques fail or provide inadequate diagnostic capability. For example, the VEI scanner can successfully scan bridge decks with a variety of different overlay types and can be operated during the day or night. Highlighting the capabilities of the VEI scanner for assessing decks with asphalt overlays, in particular, a map that was generated after testing of a two-lane asphalt-overlaid bridge deck in Nebraska is shown in Figure 3. VEI measurements were obtained at approximately 0.5-inch spacing in the longitudinal direction and 2-ft spacing in the transverse direction. Interpolation was used to populate the map between measurements. The data indicated insufficient protection of the rebar against chloride ingress, especially along the longitudinal construction joint between the two lanes and along the transverse joints at the ends of the deck. Because the map was generated in the field only a few minutes after the scanning was completed, which also required only a few minutes, the engineers responsible for this bridge were able to immediately verify through visual inspection beneath the bridge that the deck was leaking as shown in the VEI map.

As part of the work performed during the project, specifications for use of the VEI scanner and interpretation of the data were also generated to enable successful commercialization of the technology, which has been successfully licensed to a Utah start-up company. Commercial availability of this technique will allow greater diagnostic capabilities, more informed bridge deck rehabilitation planning, and associated cost savings. Additionally, information from future long-term studies will enable quantification of bridge deck susceptibility to chloride ingress and corrosion-induced deterioration over time and thereby help identify successful deck treatment strategies, for example.

In summary, the VEI scanner provides valuable data that support decision-making by bridge managers responsible for appropriately selecting among preservation, rehabilitation, and replacement options available within their bridge management programs.

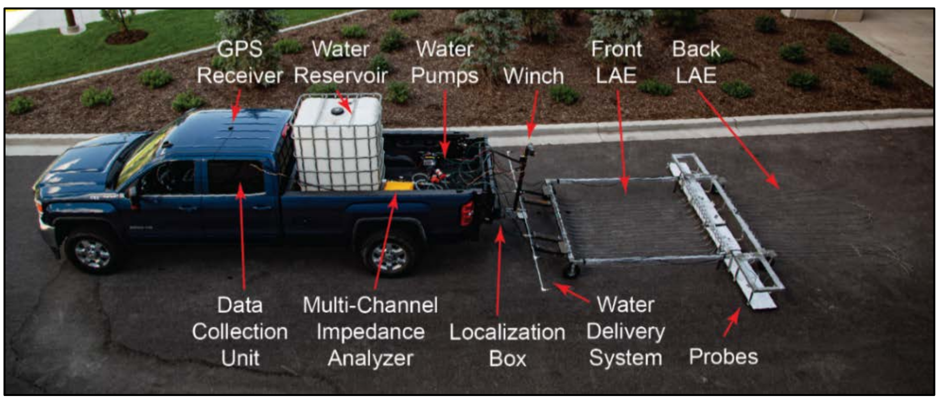


FIGURE 2 Photograph of complete VEI scanner with specific components labeled.

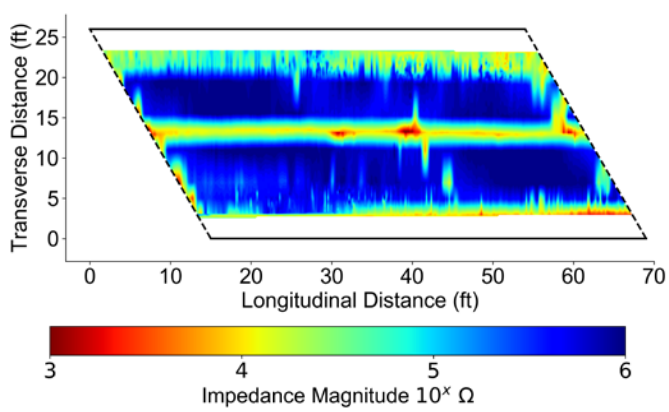


FIGURE 3 VEI map of asphalt-overlaid bridge deck indicating areas of insufficient rebar protection.

IDEA PRODUCT

The main product of this investigation was a bridge deck scanner design for quantitatively evaluating the cover protection offered to steel reinforcement against chloride ingress. This scanner, which employs a large-area electrode (LAE), can be deployed quickly on bridge decks with minimal or no stationary traffic control. The sub-products of this scanner were the following:

1. Physical specifications for the VEI scanner
2. Advanced electronics for collecting VEI data
3. Data collection framework for mapping VEI data to deck locations
4. Specifications for the use of the VEI scanner in the field

The following sections address each of these sub-products that were developed during this investigation.

PHYSICAL SPECIFICATIONS FOR THE VEI SCANNER

The VEI scanner shown in Figure 2 was constructed for quick deployment in the field and accurate and efficient data collection. A schematic of the VEI scanner is shown in Figure 4. The trailer supporting the scanner was modeled after similar scanner designs that had been deployed for impact-echo surveys [2, 3]. The main trailer components were fabricated with 2 x 2 x 1/8 in. square tube, and the extension insert connectors were fabricated with 2.5 x 2.5 x 1/4 in. square tube. The two-hinge system at the front of the scanner trailer was designed to accommodate differences in hitch heights on towing vehicles as well as irregularities in bridge deck surfaces. The scanner frame was designed so the scanner could be quickly unfolded on a job site, deployed, and then folded up after scanning was completed. The frame supporting the probe electrodes and LAEs was constructed of aluminum because aluminum is light, corrosion-resistant, and rigid enough to support the loads under which it was placed.

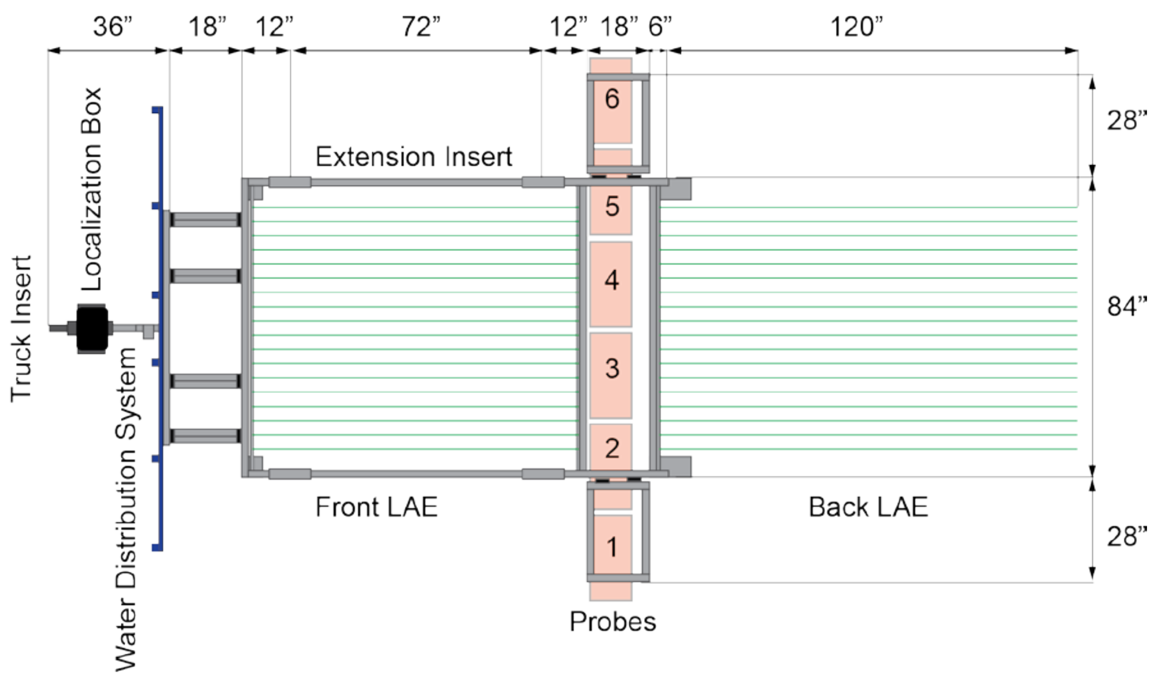


FIGURE 4 Schematic of VEI scanner including the localization unit, water distribution system, sensing probes, and LAEs as deployed in the field on bridge decks.

FIGURE 5 Photograph of VEI scanner raised for transport over short distances.

FIGURE 6 Photograph of VEI scanner reduced in overall size and folded up for transport over long distances.

The relative areas of the measurement electrodes and LAEs (about a 1:100 ratio) were designed from theoretical calculations, simulations, and laboratory experiments to ensure their adequate performance and data interpretability under practical scanning conditions [4]. Wings supporting electrodes 1 and 6 could be unfolded to increase the scanning width from 8 ft wide to 12 ft wide, as needed. When transporting the scanner short distances from one location to another, the entire system is easily raised by a winch mounted on a vertical bar located between the localization box and water distribution pipe, as shown in Figures 4 and 5. Extension inserts located on the frame supporting the front LAE were designed to allow the entire trailer system to be contracted to an even smaller size when transporting the trailer long distances as shown in Figure 6. The entire modular system was also designed so that it could be stowed in a relatively small space for transport or storage. The LAE sections and probes themselves were designed to be removed as whole components from the entire system.

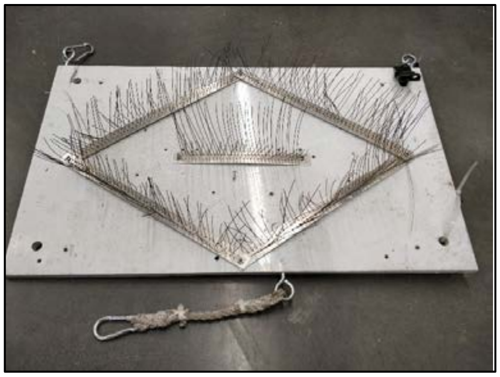
 

FIGURE 7 Photographs of guarded electrodes with the guard ring and center electrode visible (left) and in the deployed configuration (right).

A pump system in conjunction with the water distribution pipe and water sprinkler system created a thin film of water through which the rest of the system was dragged. A set of three pumps rated at a combined flow capacity of 15 gallons per minute was able to provide the recommended 0.005 gallons/ft^2 necessary for good electrical coupling. For more porous or cracked concrete or overlay surfaces, additional water may be added through multiple passes of the VEI scanner, with or without data collection, or the use of a leading vehicle equipped with a water tank or other water-dispensing device to soak the deck prior to scanning.

The physical design of the probes and electrodes was important for the scanner to operate successfully on rough bridge decks. Brush-type probes created consistent electrical connections to the bridge surfaces. Guarded probes (guard ring plus center electrode) were used to inject current as shown in Figure 7. Two LAEs were placed around the guarded probes, one in front of the probes and one behind the probes. This arrangement ensured that a good electrical connection could be made to the rebar when the scanner was crossing any joints, for example, where a break in electrical continuity was expected. Additionally, having the LAEs placed near the guarded probes reduced stray currents from the guard rings that could otherwise perturb the potential of the steel reinforcement slightly [4]. Finally, a set of four wheels mounted at the four corners of the aluminum frame provided a consistent height for the frame from which the six probe electrodes and LAE were suspended.

The scanner is shown in Figure 8 in an unfolded position with the front and back LAEs in place. Because slight perturbations of the effective area of the LAEs do not yield strong impedance changes [4], the rear LAE was designed to be dragged unconstrained. This open-ended design of the rear electrode also reduced the weight and the complexity of the folding mechanism when the trailer was stowed for travel between testing locations (earlier versions had a rigid frame that required significant complexity to fold). The parallel arrangement of the corrosion-resistant aircraft cables used as electrodes also reduced the probability of debris catching on the cables as the device moved over the bridge deck surface. The construction of the LAEs produced good electrical contact with the deck surface under a variety of surface conditions.

FIGURE 8 Photograph of front and back LAEs with the guarded probes between them.

ADVANCED ELECTRONICS FOR COLLECTING VEI DATA

Custom electronics were designed, built, and deployed for measuring VEI over the large range of electrical conditions that would be characteristic of bridge decks in the field. Each VEI measurement unit can generate excitation frequencies from 100 Hz to 1 kHz. The data from each VEI measurement unit is recorded at a rate of 98 Hz with an effective filtered bandwidth of 40 samples per second. VEI measurement magnitude can be effectively estimated from 10^3 to 10^6 Ohms. This large range allows for quantification of a variety of rebar protection systems on concrete bridge decks. The entire circuit was built by using relatively low-cost electronics (<$100) that could be easily networked. The overall schematic for the circuitry, including signal generation and measurement, is presented in Figure 9, and an example printed circuit board is shown in Figure 10.

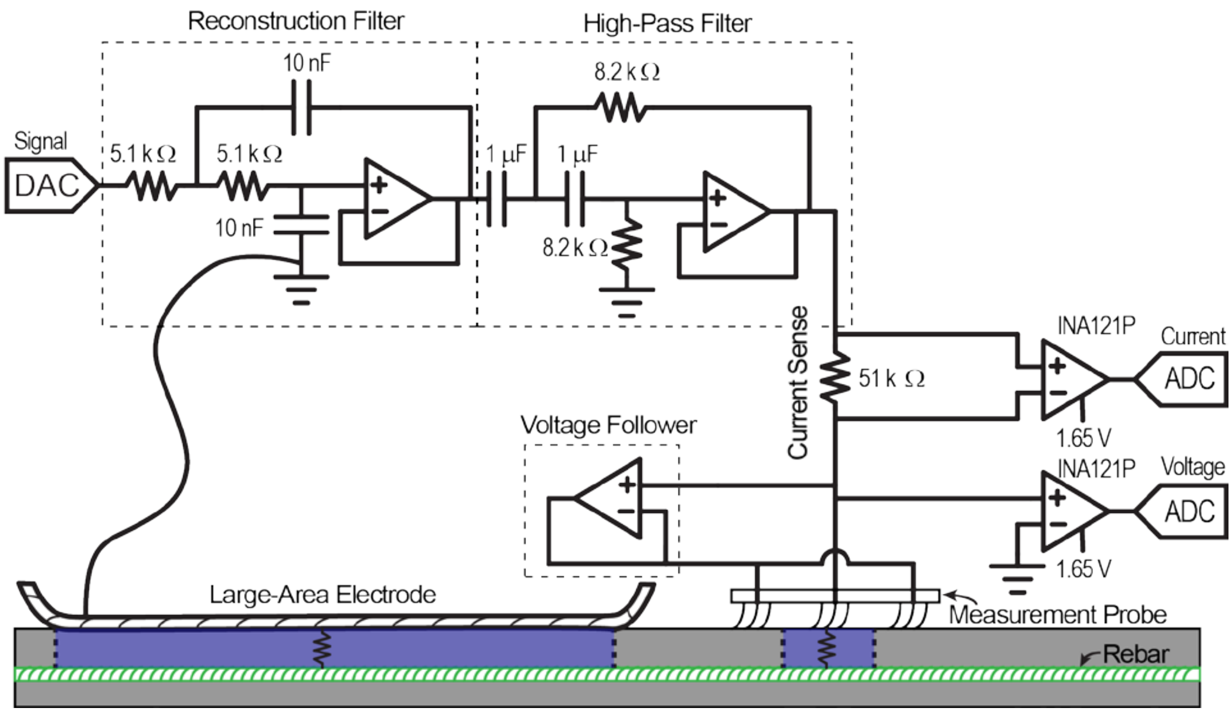


FIGURE 9 Schematic of electronic circuit used to obtain VEI measurements based on a microcontroller architecture with supporting analog components to generate signals and measure responses.

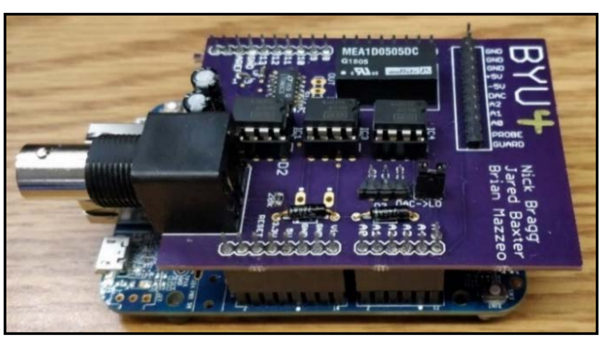


FIGURE 10 Photographs of (left) a printed circuit board for a single-channel unit used to obtain VEI measurements and (right) multiple single-channel VEI measurement units in a protected enclosure.

The signal processing scheme for each of the VEI measurement units was performed on the microcontroller unit. The microcontroller generated the necessary analog sinusoidal signals and also performed all the necessary demodulation of the signals to estimate the magnitude and phase of the voltage and current injected into the bridge deck surface. The demodulation side of the scheme is depicted in Figure 11, which shows how the signal sampled at 100 kHz is processed. Many decimating low-pass filters (LPF) are used to clean the signal and increase the resolution of the signals. The effective bandwidth of the amplitude and phase signals generated from this filtering scheme is about 40 Hz. Remarkably, all of this signal processing takes place in the low-cost microcontroller in real-time. Pre-computation of the sinusoidal components reduces the necessity of repeatedly computing the trigonometric operations. This scheme does require extensive use of the floating point capabilities of the microcontroller. To more effectively use the limited capabilities of the microcontroller and avoid disruption of signal timing, direct memory access features of the microcontroller in both signal generation and sampling of signals are utilized heavily. This clever signal processing scheme allows the entire signal processing chain to take place on the microcontroller and achieve the high sampling rates and large dynamic range of measurements that are necessary for the VEI scanner.

Each of the single-channel VEI measurement units was powered by a universal serial bus (USB) hub that itself was powered by a portable rechargeable battery. These units were also configured and controlled through this USB hub, through which measurements were also returned. Use of a USB hub enabled many different VEI measurement units to be easily powered, connected, and addressed in parallel. Cables were routed from each of the VEI measurement units to the guarded probe electrodes to measure the currents through the center electrodes and to drive the guard rings. The units were compact enough for all of them to be easily placed in a single, protected enclosure as shown in Figure 10.

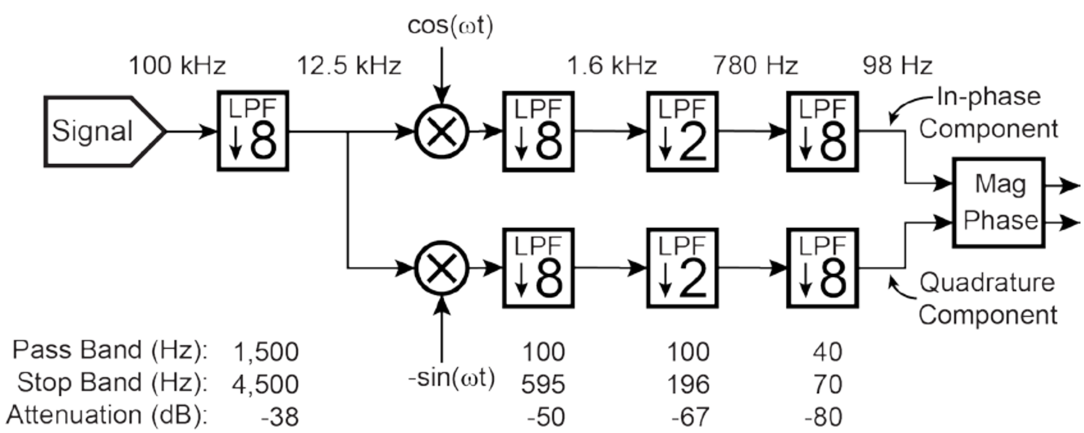


FIGURE 11 Schematic of the signal sampling scheme, as well as filtering and demodulation of the signal to estimate the in-phase and quadrature components of the applied sinusoidal signals.

DATA COLLECTION FRAMEWORK FOR MAPPING VEI DATA TO DECK LOCATIONS

The data collection framework for the VEI scanner was custom-built to allow localization to be performed quickly after obtaining VEI data in the field. An overall schematic of this data collection framework is displayed in Figure 12. The data collection framework consisted of multiple single-board computers (SBC) that were linked together to acquire data from many different channels. A photograph of the rack that held all of these units is shown in Figure 13. The VEI measurement units were individual channels configured specifically to log their data in this framework synchronized with positioning data acquired from a global positioning system (GPS), a light detection and ranging (LiDAR) system, and a high-definition camera. After a scan was completed, the data could all be downloaded to a master controller computer by requesting the data from the different SBCs through the network switch.

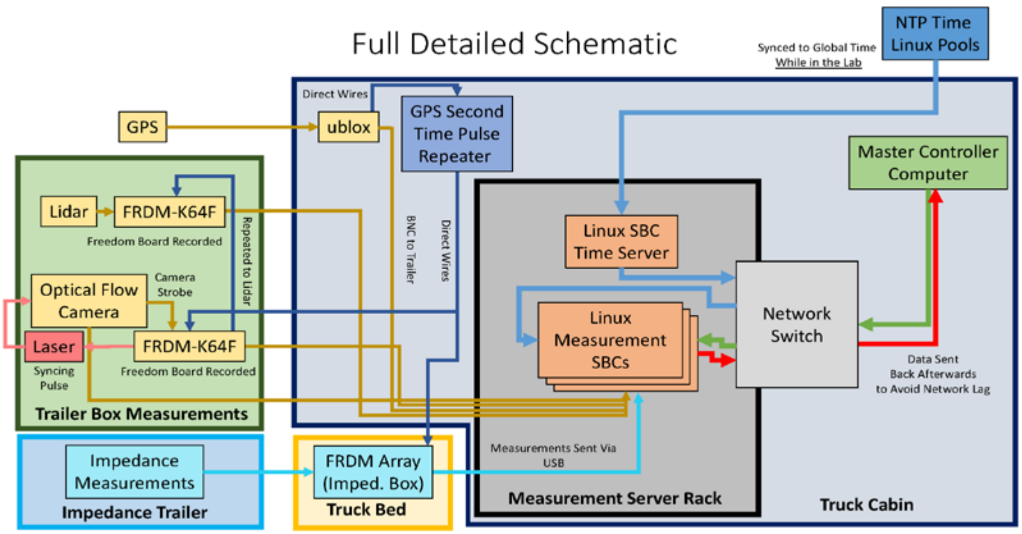


FIGURE 12 Schematic of the data collection framework for the VEI scanner, with VEI, GPS, LiDAR, and camera measurements being recorded on different SBCs during scanning.

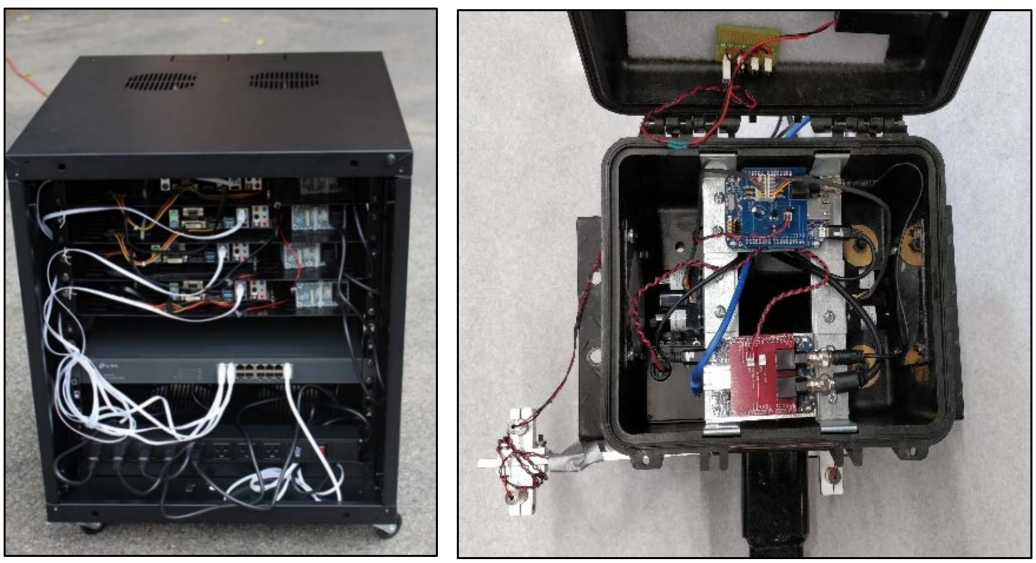


FIGURE 13 Photographs of (left) modular data collection system in which the SBCs are placed at the top of the rack, the network switch is in the middle of the rack, and power distribution and batteries are at the bottom of the rack and (right) localization box containing a laser ruler, two LiDAR measurement units, and a high-definition camera used during scanning.

A key component of this data collection framework was a box containing the different measurement units that was placed between the VEI scanner and the towing vehicle. This localization box is shown in Figure 14. In the box is a microcontroller board that interfaces with two single-channel LiDAR units. These LiDAR units were positioned with quartz windows through which they could measure the distance to the parapet walls on either side of the bridge. Additionally, the box contained a high-definition camera pointed downward at the deck surface. In conjunction with this camera was a set of laser diode units that created a visible distance measurement on the deck surface. The camera and lasers formed an additional optical flow system that could compute the distance traveled.

In a post-processing algorithm, the differential global positioning system (DGPS) data were augmented with the LiDAR measurements and the entrance and exit timings provided by the camera to estimate the position of the VEI scanner on the bridge deck. More specifically, positioning relied on a continuous-discrete extended Kalman filter with a Rauch-Tung-Striebel smoother. The states of this system were the longitudinal location, transverse location, and heading of the moving platform. Additionally, the longitude and latitude of the bridge origin, the bridge width, and the orientation of the bridge were appended to the state space as biases and were also estimated. The states of this system were propagated in continuous time through a simple velocity-based motion model using Euler integration and a first-order interpolation for the sampled velocity obtained from the GPS information. Combining all these data streams in this framework allowed the system to accurately map impedance data to specific positions on the bridge deck. A VEI map generated from this scheme is presented in Figure 3.

In general, this data collection system enabled accurate tracking of the scanner position on bridge decks. At normal scanning speeds of approximately 3 mph, VEI measurement locations were spaced approximately 0.5 in. apart in the longitudinal direction and approximately 2 ft apart in the transverse direction, matching the spacing of the probes on the scanner. As advanced GPS and other positioning technologies become less expensive, they can be incorporated into future versions of the VEI scanner to further increase the localization accuracy and stability.

SPECIFICATIONS FOR USE OF THE VEI SCANNER IN THE FIELD

A key component of this project was the development of specifications for use of the VEI scanner in the field. Developed through direct field testing experience on numerous concrete bridge decks, these specifications are intended to allow users to more successfully deploy the technology and engineers and managers to better interpret the results.

Recommended field applications for VEI scanning	Recommended field applications include (1) assessment of bridge deck overlay condition (asphalt, epoxy, latex-modified concrete, and polyester polymer concrete overlays have already been tested) to assess the potential for water and chloride leakage through the overlays and concrete cover, (2) assessment of leaks through non-visible membranes between asphalt overlays and concrete deck surfaces, and (3) assessment of bare concrete cover condition (no overlay). VEI maps can guide destructive sampling that may be specified to determine, for example, chloride concentrations at points of apparent leakage.
Resolution of VEI data appropriate for the recommended applications	VEI measurements should be obtained at a spacing not exceeding 2 ft in both the longitudinal and transverse directions.
General equipment set-up to ensure proper operation in advance of VEI scanning	Recommended protocols include (1) obtaining sufficient water necessary for all passes before starting so that VEI scanning operations can continue uninterrupted, (2) placing LAEs and measurement probes in their scanning positions on the trailer after arriving on site so that the probes can be simply lowered by a winch or hydraulic system, (3) performing

	tests to ensure that each probe channel is functioning properly before operation of the VEI scanner, and (4) maintaining a thin film of water on the deck surface during scanning to maintain good electrical contact with the deck.
Use of LAEs	LAEs are placed in the front and back of the measurement probes to ensure continuous connectivity of the scanner to the rebar over any breaks in electrical continuity within the rebar. The LAE area should be at least 60 times greater than the area of a single measurement probe. In the preferred arrangement of the VEI scanner, the front LAE is placed within a rigid frame, while the back LAE is not within a frame.
Checks of the data collection framework before VEI scanning	Prior to the initial scan of a bridge deck, each sensor component should be tested. One operator can manually trigger each sensor component while another operator can monitor the responses. Normal GPS response is evaluated by driving the towing vehicle a few feet forward or backward. Normal LiDAR response is evaluated by placing a hand first in front of the right LiDAR and then in front of the left LiDAR. Normal high-definition camera response is evaluated by placing a foot within the viewing window of the camera. Normal measurement probe responses are evaluated by shorting a strand of the LAE to the center electrode of each probe.
Amount of water applied to the deck prior to VEI scanning	A sufficient amount of water should be applied to the deck prior to VEI scanning to ensure a substantially stable moisture content, with moisture having penetrated porous areas and cracks. Although the amount of water to be added depends on the overlay type and current moisture content, typical values are 0.005 gallons/ft^2 for bare decks, epoxy overlays, latex-modified concrete overlays, and polyester polymer concrete overlays and 0.015 gallons/ft^2 for asphalt overlays.
Time between initial water application and VEI scanning	Enough time between the initial water application and VEI scanning of the deck should pass to allow the deck to reach a stable moisture content. Based on field results, recommendations were developed for different types of overlays. Bare concrete bridge decks and latex-modified concrete overlays typically require less than 1 minute

	of soaking, epoxy and polyester polymer concrete overlays require about 10 minutes of soaking, and asphalt overlays require upwards of 15 minutes of soaking. The required time depends on the porosity, interconnectivity, and tortuosity of the deck surface. Good comparisons of VEI data collected from consecutive scans generally indicate a satisfactory soaking time.
Speed of VEI data collection for satisfactory resolution	The VEI scanner should traverse the deck at walking speed, or less than approximately 4 mph, to ensure satisfactory resolution.
Amount of water to apply to the deck during VEI scanning	To ensure adequate electrical coupling, a continuous thin film of water that can persist until the measurement probes pass over it should be placed on the bridge deck surface. Approximately 0.005 gallons/ft^2 of water is sufficient in most cases, but the amount should be increased for VEI scanning in conditions of wind, high temperature, or low humidity.
Number of VEI scanning passes per lane	A minimum of two passes per lane is recommended to establish the stability of the VEI measurements and to ensure that proper soaking was achieved. The first pass can be used to soak the deck and obtain preliminary measurements, while the second pass can be used to obtain final data. If an additional vehicle equipped with a water tank or other water-dispensing device is used to soak the deck prior to scanning, one pass is usually sufficient.
Interpretation of collected VEI data (including expected degree of repeatability)	Areas that have low VEI measurements (at least one order of magnitude below the average) should be investigated for possible leakage, deterioration, or damage. In general, VEI values below approximately 10^4 Ohm indicate areas of possible concern and may warrant further investigation.

The physical design, advanced electronics, data collection framework, and usage specifications ensure that the VEI scanner can be successfully deployed in the field, and the results are expected to provide bridge owners with actionable data for rehabilitation planning. The development of the VEI scanner is a significant advance in bridge inspection technology, providing a new means to assess the protection offered to rebar on concrete bridge decks, especially those with overlays.

CONCEPT AND INNOVATION

Electrical impedance is a suitable method for characterizing the protection provided by concrete against chloride ingress because the electrical impedance of concrete is largely a function of the same properties of the concrete matrix and the pore water that influence chloride ingress within concrete. A concrete matrix with high porosity characterized by high interconnectivity and low tortuosity allows for the passage of high amounts of electrical current and would have low impedance compared to a concrete with low porosity characterized by low interconnectivity and high tortuosity, all other factors constant. Regarding the pore water, high ion concentrations and high temperatures allow for the passage of high amounts of electrical current through the concrete due to the high abundance and mobility of current carriers within the pore water.

Despite the value of impedance measurements in this context, traditional methods for measuring the impedance of the concrete cover on a bridge deck are limited in several respects. These methods, which typically involve injection of a horizontal current, parallel to the surface of the concrete, and subsequent measurement of the voltage drop across the electrodes, are prone to operator error to various degrees and subsequently require very strict measurement protocols for meaningful data to be obtained [5]. For this reason, the results of horizontal resistivity testing are commonly supplemented with other test data in condition assessments of concrete bridge decks.

An alternative technique involves injection of a vertical current, perpendicular to the surface of the concrete, and measurement of the voltage drop between the connection to the steel reinforcement and the surface of the concrete. Vertical methods have the potential to directly quantify the degree of protection against chlorides provided by the reinforcing steel by the concrete cover and by any rebar coatings and/or deck surface treatments. Instruments to measure vertical impedance were first developed and deployed in 2012 to explore the apparent superiority of the vertical method for more accurately characterizing complete deck protection systems [6]. Following successful field tests using a rudimentary electrical impedance system, many laboratory tests were performed to develop signal criteria to evaluate cover protection. These efforts resulted in the selection of signals between 100 Hz and 1 kHz because of the sensitivity of impedance measurements in this frequency range to changes in concrete bridge deck properties that directly affect the protection offered to steel reinforcement [7]. A rolling VEI system was then constructed and used in some preliminary field studies to investigate the benefits of using VEI for evaluating bridge decks with asphalt overlays [8].

Three innovative concepts were created to specifically make VEI measurements more practical in application:

1) Use of an LAE to replace a direct electrical connection to the steel reinforcement
2) Redesigned electrodes for continuous measurements
3) Advanced electronics for VEI measurements and localization

USE OF AN LAE TO REPLACE A DIRECT ELECTRICAL CONNECTION TO THE STEEL REINFORCEMENT

Direct electrical connections to the steel reinforcement are necessary for many electrochemical and electrical measurements on concrete bridge decks, and installing such electrical connections can require significant effort. A process for installing a tapped electrical connection is shown in Figure 14. As the sequence of photographs illustrates, installing a tapped connection can be a time-consuming process, and a wire running from the tap location to the test instrument must be constantly managed. Furthermore, after the testing is complete, the holes in the overlay and deck must be patched, and, depending on the situation, the damage may not be fully reparable, such as when asphalt membranes are penetrated during the coring process.

(a) (b) (c) (d)

FIGURE 14 Sequence of steps for creating a direct electrical connection to steel reinforcement, including (a) locating the steel reinforcement through a thick asphalt overlay using ground penetrating radar, (b) coring through the overlay, (c) drilling through the concrete to expose the steel reinforcement, and (d) connecting a spool of wire to the exposed steel to provide a direct electrical connection to the test instrument.

In addition, a significant but frequently unverified assumption is made when a direct electrical connection is used in practice. The assumption is that the steel reinforcement is electrically interconnected with relatively low impedance from the tapped electrical connection to any point across the deck. However, as one example, the presence of epoxy coatings on rebar can compromise the electrical continuity of the rebar and violate this assumption. For this reason, using an LAE, which moves across the deck with the measurement probes, is actually a more attractive option for specific test methods, such as VEI scanning.

Use of an LAE overcomes the need for a direct electrical connection to the steel reinforcement. For successful, practical VEI measurements in the field, a connection with a low electrical impedance to the steel reinforcement is needed. As demonstrated in Figure 15, a direct connection can be replaced by an LAE if the impedance between the LAE and the steel reinforcement is low enough. Given that the electrical impedance between the LAE and the deck surface is affected by the surface area of the LAE, where the electrical impedance decreases with increasing LAE surface area, an LAE can form a low-impedance connection to the steel reinforcement if the area is much larger than the area of the measurement probes. Application of this important idea not only eliminates the need for a tapped electrical connection but also enables testing from a continuously moving platform.

FIGURE 15 Illustration of the technical principle of an LAE forming a low-impedance connection (right) to the steel reinforcement to replace a direct electrical connection (left) to the steel reinforcement.

REDESIGNED ELECTRODES FOR CONTINUOUS MEASUREMENT

VEI scanning from a continuously moving platform required a new measurement probe design. As described in Bartholomew et. al. [6], early VEI measurements were performed by manually moving a large, static probe from point to point on a bridge deck. Because the guard ring and center electrode were made of foam, which was not possible to slide along the concrete surface, the probe had to be lifted and carried between measurement points.

Incremental improvements in the probe design were accomplished with the configurations shown in Figure 16, which included foam-roller electrodes and chain electrodes. In field testing, the foam rollers fouled easily and did not maintain consistent electrical contact with the deck surface when spalled concrete or potholes were traversed. While chains were more capable of maintaining contact along uneven deck surfaces, they intermittently lost electrical connection due to occasional separations of adjacent chain links under vibration, and they also collected significant amounts of debris. In addition, their excessive weight and tendency to become entangled during transport and testing was problematic.

Successful designs were eventually achieved using a flexible brush for the measurement probe and parallel aircraft cables for the LAEs. These improved designs, which are shown in Figure 7 as part of the final product description, overcame all of the problems experienced with the earlier designs. They were also lighter than the previous electrode configurations, which enabled use of a simpler trailer frame design with lower structural capacity.

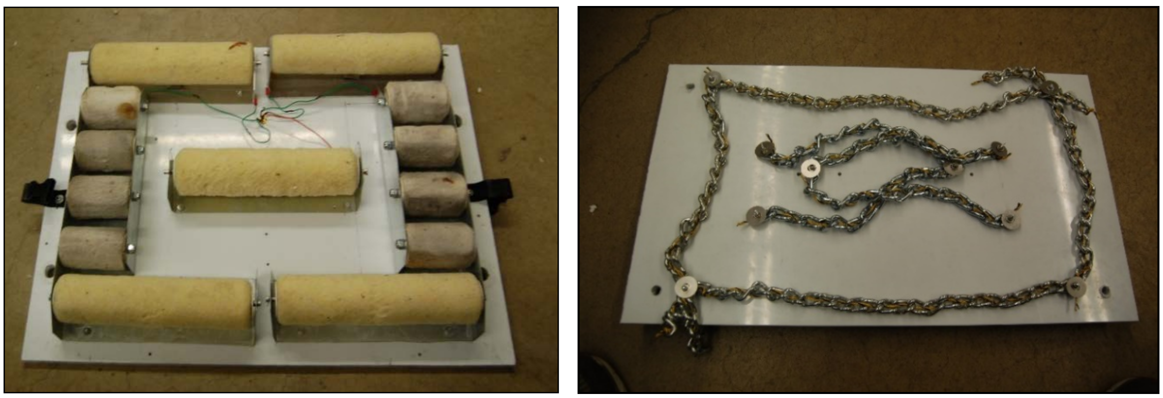


FIGURE 16 Photographs of (left) a foam-roller electrode and (right) a chain electrode.

ADVANCED ELECTRONICS FOR VEI MEASUREMENTS AND LOCALIZATION

Almost all laboratory electrochemical impedance analyzers use a transimpedance amplifier arrangement to measure the current through the electrodes. This arrangement is convenient in the laboratory because the transimpedance amplifier forms a virtual ground through which all the current in the system can flow. This circuit arrangement also allows for significant auto-ranging capability, as well as simplicity. In addition, the signal generation is made easier because the current measurement is not in series with the output. However, this circuit arrangement does not work properly on a concrete bridge deck. A transimpedance amplifier arrangement assumes that all the current in the system comes from the signal source. Because the steel reinforcement is not actually isolated from the real ground, nor from other electrically interconnected parts of the bridge structure, current measurements from the rebar are quite noisy and suffer from significant current fluctuations. Additionally, guard ring currents and center electrode currents will combine with each other and cannot be separated at the ground terminal connection, thus further confounding any potential transimpedance circuit configurations from a practical perspective. Because typical laboratory instruments could not be used in the field for this reason, new electronics needed to be designed for the VEI scanner.

The solution to VEI measurements on concrete bridge decks is the use of a high-side current measurement as illustrated in Figure 9. In this analog circuit configuration, the current measurement is performed on the signal source side of the electrodes, effectively measuring the current injection into the system. No transimpedance amplifiers are employed to create virtual electrical grounds; the steel reinforcement is simply a potential reference for the high-side measurement. The current going into the test system is estimated by running the current through a resistor or some other electrical element. For simplicity, a high-precision resistor was used in this system. While this approach leads to a voltage potential that is not quite the same as that generated at the source, the current going through the center electrode of the measurement probe is able to be estimated exactly. Precision instrumentation amplifiers must be used because the potentials at the different terminals of the current-sensing resistor will change based on the load that the signal is applied to interrogate. By using voltage followers at the probe side, guard rings can also be effectively and easily driven. Effectively, this VEI configuration is truly a high-side, current-sensing, guarded electrode measurement.

Designing a microcontroller configuration to be able to perform many signal generation and signal processing functions required a significant effort. The FRDM-K64F evaluation board platform was ideal for this effort because it had digital-to-analog converters, analog-to-digital converters, floating point capability, and direct memory access. If a low-cost platform such as the FRDM-K64F had not been used and modular instruments were employed, the cost of the hardware would have been two orders of magnitude higher than it was. The architecture is demonstrated as part of the product description, but the advanced electronics should be acknowledged as a significant reason why this project was innovative and successful.

In addition to the VEI measurement circuitry, low-cost positioning was obtained via DGPS, LiDAR, and camera measurements. The cost of these sensor systems has decreased considerably, such that these systems now cost only a few hundred dollars, which is also orders of magnitude less than similar products available just a few years ago. Combining all of these measurements using networked SBCs simplified data acquisition and increased the reliability of the data collection scheme. Because individual localization measurements were routed through dedicated USB channels on SBCs running single threads for data acquisition, the potential for bus collisions and competing software threads was eliminated. This architecture can also be scaled up to include additional localization sensors or other measurements in parallel with the VEI measurements.

INVESTIGATION

The investigation was carried out in two stages of development. These stages allowed for prototyping and improvement of the completed VEI scanner and then deployment of the VEI scanner in the field.

STAGE I DEVELOPMENT

The overall design of the arrangement of the LAE and the probes was an important task from the beginning of this project. The LAE needed to be able to cover a large area with two large, independent sections to ensure continuous connectivity of the scanner to the rebar over any breaks in electrical continuity within the rebar in a concrete bridge deck. Additionally, the apparatus needed to be readily deployable by a single person. During the course of this stage, the electrode assembly and configuration evolved significantly, from the single LAE made of chains mounted in a heavy wooden frame to double LAEs made of aircraft cables mounted in or to an aluminum frame. In addition, the scanning width increased from 8 ft to 12 ft. Figure 17 highlights these developments.

As described in earlier sections, the design of the measurement probe evolved from a static foam electrode to a foam-roller electrode to a chain electrode to, finally, a flexible brush electrode. Individual mechanical connections from each probe to the trailer frame relied on flexible straps and clips to allow for variation in height from a bridge deck surface to the trailer frame during scanning.

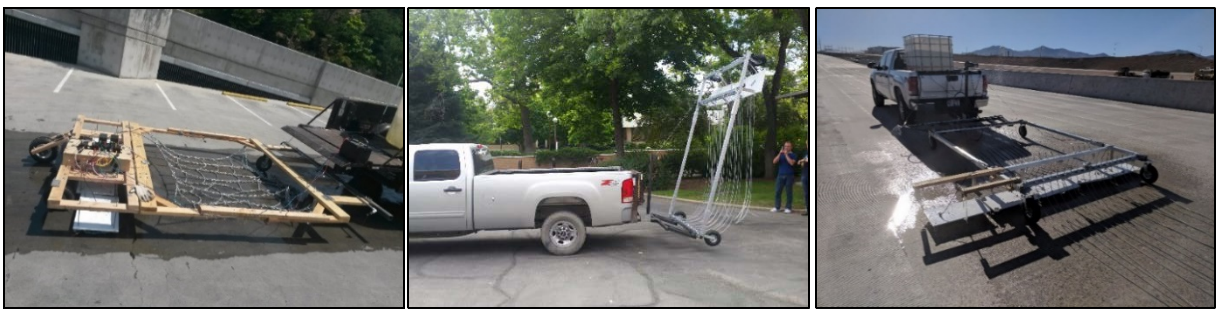


FIGURE 17 Stage I evolution of trailer design from (left) single LAE made of chains mounted in a heavy wooden frame to (middle) double LAEs made of aircraft cables mounted in or to an aluminum frame to (right) a preliminary wooden wing design that increased the scanning width from 8 ft to 12 ft.

The electronics were custom-designed in this stage to be able to provide the desired frequency spacing and high-side impedance measurements. Results showing the speed at which measurements can be taken and the accuracy of those measurements are shown in Figure 18. The circuit was designed so that many measurements over large orders of magnitude can be taken, with less emphasis on the absolute accuracy of those measurements. The design was constrained by the inherently noisy electrical conditions of concrete bridge decks and the desire to be able to rapidly scan large areas of the deck at interrogation frequencies in the hundreds of Hz.

Localization of the measurement data proved to be a considerable challenge throughout this project, and many of the project resources in Stage I were devoted to developing solutions to this challenge. Localization was achieved through a combination of DGPS, LiDAR, and camera measurements. The physical hardware developed to address this challenge is shown in Figure 13. The key for timing was that the DGPS generated accurate time pulses that were then relayed to the array of measurement devices, including the LiDAR units and optical tracking camera. The time pulses of the DGPS unit synchronize the measurements. In this stage, image correlation was used to estimate vehicle movement. As shown in Figure 19, a digital processing scheme using a Kalman filter then combines the positioning data and demonstrates that this combination of hardware and software can achieve sub-foot localization. This unique platform was a useful outgrowth of the research to make this system practical and addressed the limitations of other scanning solutions.

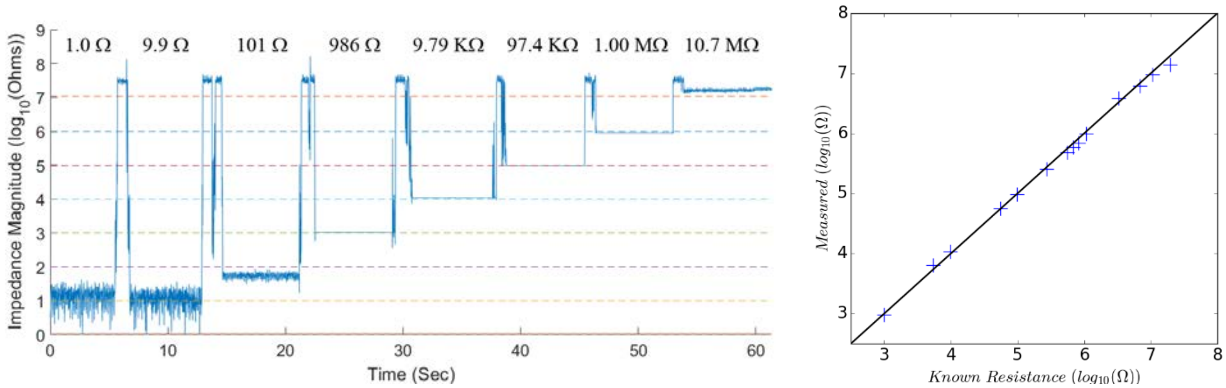


FIGURE 18 (Left) time plot of probe circuitry measurements on known resistors showing readouts at high rates (~98 Hz) when different resistors are switched in and out of the measurement circuit and (right) plot of accuracy of measurements at 190 Hz with respect to known, calibrated resistors over orders of magnitude corresponding to typical bridge deck impedance conditions.

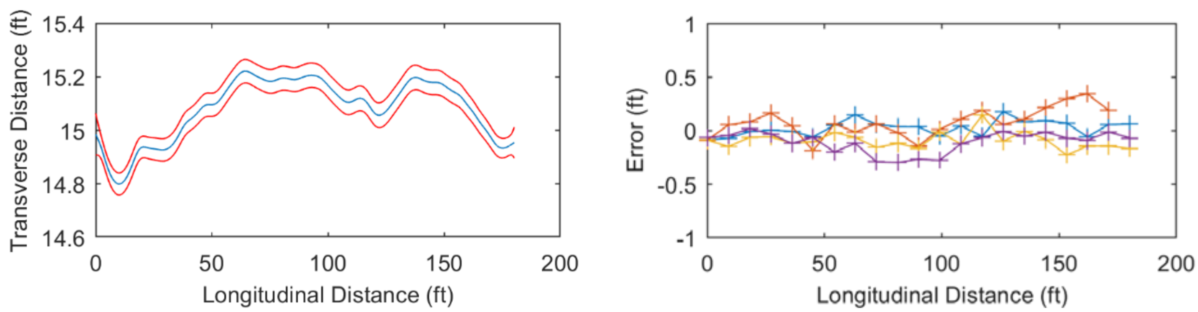


FIGURE 19 (Left) Kalman filter output showing the trajectory of a testing path with defined upper and lower error bounds and (right) error calculations (differences between localization estimates and actual position) for four repeated test paths compared with ground truth at approximately 9-ft intervals.

A significant development during the course of Stage I was the establishment of design protocols and performance criteria for the use of VEI measurements obtained using an LAE instead of a direct electrical connection to the rebar. The criteria were used to assess (1) how the impedance measured using an LAE would be related to the impedance measured using a direct electrical connection and (2) how sensitive the impedance measurements would be to changes in the area of the LAE. As these parameters would govern the efficacy of the technique, simulating these effects was important.

An analytical model (AM) and a finite element model (FEM) in ANSYS were developed to approximate the various contributions to impedance (electrode-electrolyte impedance, water layer, concrete layers, rebar, and LAE effects) and to simulate the performance of various electrode configurations. Simulated concrete resistivity values ranged from 10^2 to 10^6 Ohm-m, and water resistivity ranged from 2 to 2×10^3 Ohm-m. Figure 20 illustrates the geometry of the systems that were analyzed and simulated as well as one of the important results of those studies. The area ratio, which is the ratio of the area of the LAE to the effective area of the probe, was studied extensively under a variety of concrete resistivity conditions. Importantly, once the area ratio was on the order of about 30, the gains from a larger LAE diminished in that the measured impedance asymptotically converged to a stable value close to the value obtained from the tapped connection. These curves in Figure 20 were used to establish correction factors for the measured impedance given a particular experimental area ratio [4]. The area ratio for each of our two LAEs was approximately 50, for a total area ratio of about 100 when the LAE areas were combined, so we could be quite sure that, for the range of conductivities that we expected in practice, the area ratio would be sufficient to be able to measure the effective VEI almost as if it were a tapped connection even while traveling over transverse bridge deck joints. These simulations confirmed the intuition that we had developed about the theory related to LAE usage.

To further confirm that the LAE approach would be viable for VEI testing on actual bridge decks, experimental validation was performed on a laboratory slab taken from a decommissioned bridge deck and on an upper deck of a concrete parking garage structure. In both cases, the area of the LAE was incrementally increased by adding electrode area elements. In this way, the area ratio could be adjusted to examine its effect on the measured impedance. A photograph of the laboratory test and plots of the results are shown in Figure 21. These results agreed nicely with the numerical simulations in that they showed that, as the area ratio increases, the measured impedance appeared to converge to a particular value. Natural variation across an actual, weathered concrete specimen was expected to have more variation than that observed in the simulations, which ensured uniformity across the slabs. Indeed, a ratio of approximately 100 seemed to be more than adequate for these types of VEI measurements.

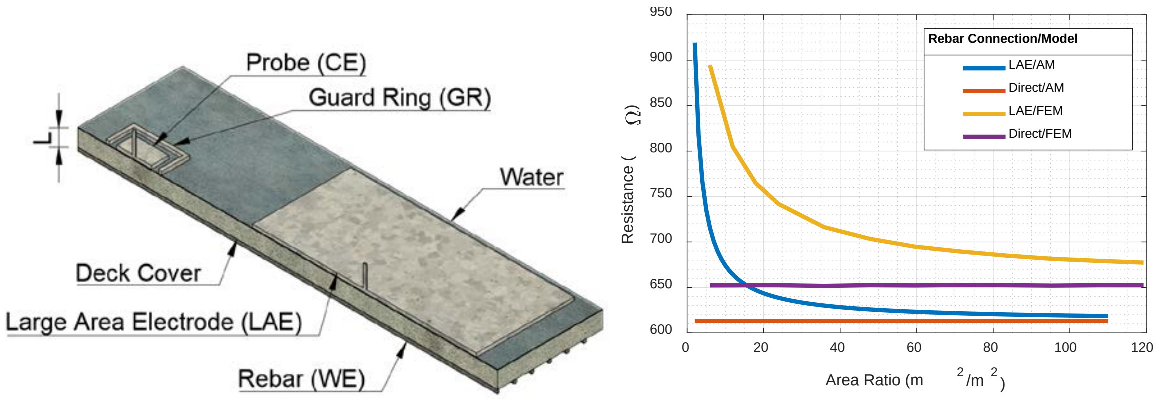


FIGURE 20 (Left) 3D model of a vertical impedance configuration where an LAE replaces a tapped connection to the steel reinforcement used for development of both an AM and FEM of VEI for multiple electrode configurations and (right) results of analysis and numerical FEM experiments for direct and LAE connections using the two models showing that, as the area ratio increases, the resistance of the LAE connections asymptotically approach the direct connections and that, above a ratio of about 30, the influence of changes in the area ratio is significantly decreased.

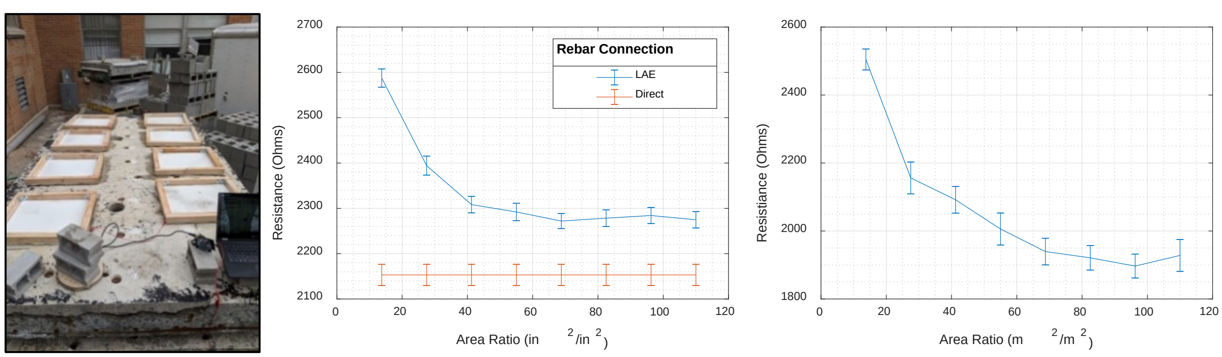


FIGURE 21 (Left) experimental configuration of discrete LAE elements on a slab in the laboratory, (middle) results of the experiment in the laboratory that show the expected convergence of the resistance of the LAE connection to a stable value greater than the direct connection to the rebar, and (right) results from a similar LAE area ratio experiment performed on an upper deck of a concrete parking garage, for which a good tapped electrical connection to the underlying rebar was not available, showing decreasing impedance that fluctuates around a stable value.

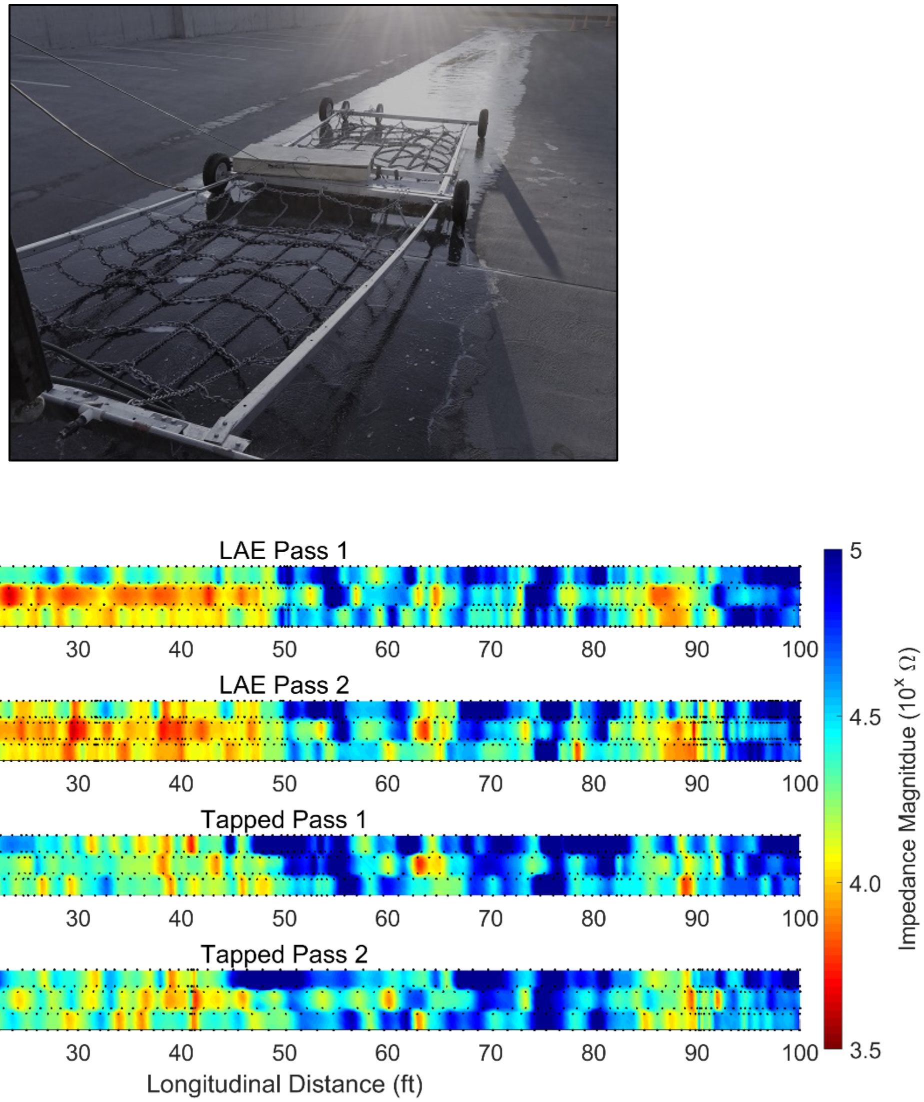


FIGURE 22 (Top) early prototype version of VEI scanner deployed on an upper deck of a concrete parking garage and (bottom) results of four-channel experiments showing good reliability and comparability between the LAE and tapped experiments.

Deployment of new technology in the field to accelerate development has been a hallmark of our research group and essential to validating the VEI technology for this project. Multiple iterations of the device were tested in the field in Stage I to discover both the practical and theoretical limitations of the devices for achieving satisfactory performance, as well as to inform specification development. For example, an early prototype of the LAE system was deployed to examine reliability of data collection and to compare against a tapped measurement; as shown in Figure 22, an area of known deterioration was included in the first 50 ft so that the reliability of the measurement could be established. In these experiments, the impedance of the LAE connection to the rebar actually appeared to be less than that of the tapped connection.

The most extensive experiment conducted during Stage 1 was testing of the longest bridge (3390 ft) in the state of Utah. Highlighted in Figures 23 and 24, this experiment was unique for multiple reasons. Because of the great length of the bridge deck, traffic control was conducted in a rolling fashion along the bridge. Hundreds of gallons of water were also needed to conduct the test, so a water tank trailer was rented and provided water soaking in advance of the main VEI testing vehicle. Figure 23 shows the water tank trailer in front of the truck towing the impedance trailer and also shows the tank in the bed of the truck that supplied water to the on-board sprinkler system. Many lessons were learned through this testing, including the need for (1) larger video buffers because they would fill up after traveling more than 1000 ft at a slow speed, (2) modification of the trailer and hitch to improve lifting and moving the trailer, and (3) many modifications to the localization and synchronization algorithms. Furthermore, because the bridge had an epoxy overlay placed over a latex-modified concrete overlay that was deteriorating, the testing enabled evaluation of a variety of deck defects. One of the interesting conclusions of this study was that low VEI measurements did not uniquely identify the type of defect; that is, low VEI measurements can have multiple causes. For example, if there was a high chloride concentration at the top mat of reinforcing steel, the VEI was generally low; however, a low VEI did not necessarily mean that the chloride concentration at the top mat was high. In these latter cases, the low VEI was possibly associated with recent cracking that would be expected to be a predictor of high chloride concentration in the future, depending on the level of exposure of the concrete to chloride-based salts. Finally, the VEI data collected on this bridge deck were extremely useful for guiding subsequent destructive sampling designed to assist the bridge owner with determining the appropriate scope of deck rehabilitation.

The field tests performed in Stage 1 of this research led to improvements in both the trailer design and the electronics used for data collection. In addition, observations about the amounts of water required to achieve a continuous water film, the speed of data collection, and other aspects of VEI testing were useful in developing initial usage specifications.

FIGURE 23 Photograph of VEI scanner deployed on the longest bridge deck in Utah.

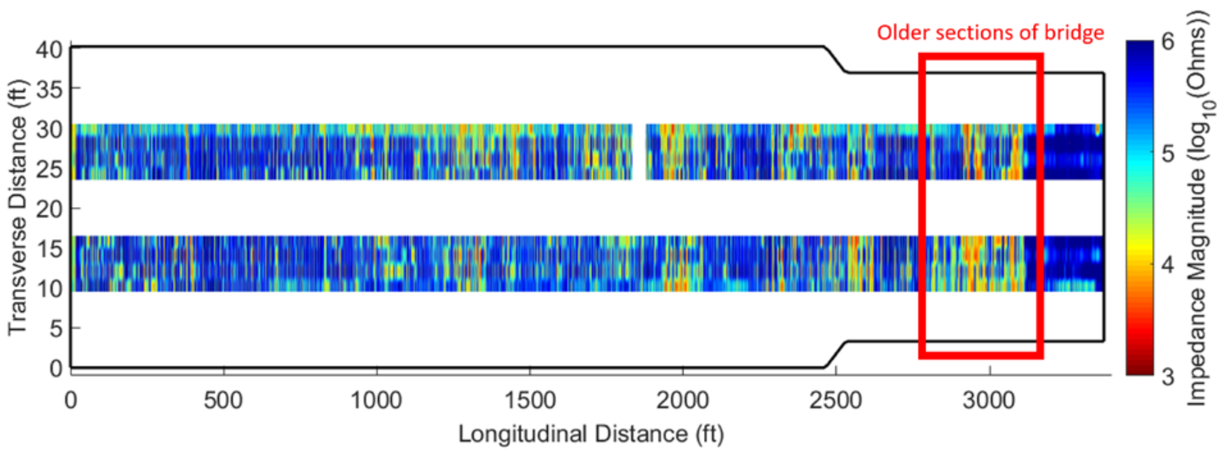


FIGURE 24 Impedance map generated from scanning of both lanes of the longest bridge deck in Utah in which older sections of the bridge (not known at the time of testing) displayed lower impedance, generally indicating that the deck had deteriorated more significantly in those areas.

STAGE II DEVELOPMENT

The goal of Stage II was extensive field testing to establish the specifications necessary for regular commercial deployment of the scanner after the project was completed. Bridges in both Utah and Nebraska were scanned, and significant revisions to the scanning protocols were made

Bridge Decks with Polymer Concrete Overlays in Utah

The apparatus was deployed in Salt Lake City to test two bridge decks with polyester polymer concrete (PPC) overlays, as shown in Figure 25 (left), that were placed in 2016. The purpose of this field testing was to use the impedance apparatus to determine the effectiveness of the PPC overlays for protecting the bridge deck from chloride ingress, as well as to evaluate the specifications outlined at the end of Stage I. An earlier version of the VEI scanner had been used to scan the decks before the PPC overlay was placed, so VEI data from before and after PPC application could be compared.

The results of VEI scanning are shown in Figure 26 for both bridge decks. Because traffic control requirements limited the scanning area to the right lanes closest to the parapet walls, as shown in Figure 25 (left), a 50-ft-wide area in the center of bridge deck 1 was not scanned. Consequently, for the purpose of presentation only, the omitted area is not shown in the impedance maps. After the PPC application, bridge deck 1 clearly had a lower average impedance than bridge deck 2. On bridge deck 1, hydrodemolition was used to scarify the bridge deck surface to a depth of approximately 0.75 in. prior to overlay placement. The hydrodemolition process resulted in a very uneven surface with many peaks and troughs as shown in Figure 25 (right). When the overlay was placed, the PPC mixture filled the troughs but barely covered the peaks, resulting in a comparatively thick overlay in some places and a very thin overlay in other places. The places where the overlay was thin were then more susceptible to cracking and exhibited much less protection from chloride ingress as evidenced by the lower impedance values that were measured. Indeed, the impedance maps suggest that the protection after hydrodemolition and overlay was, on average, lower than that before hydrodemolition and overlay.

On bridge deck 2, the PPC overlay was placed at a uniform thickness of approximately 0.75 in. across the entire deck, and the impedance testing demonstrated that this approach was very effective; the impedance of bridge deck 2 measured after overlay placement was about an order of magnitude higher than that measured before overlay placement.

FIGURE 25 (Left) impedance testing of an outer lane on a bridge deck with a PPC overlay in northern Utah and (right) scarified surface of the same bridge deck prior to application of the PPC overlay.

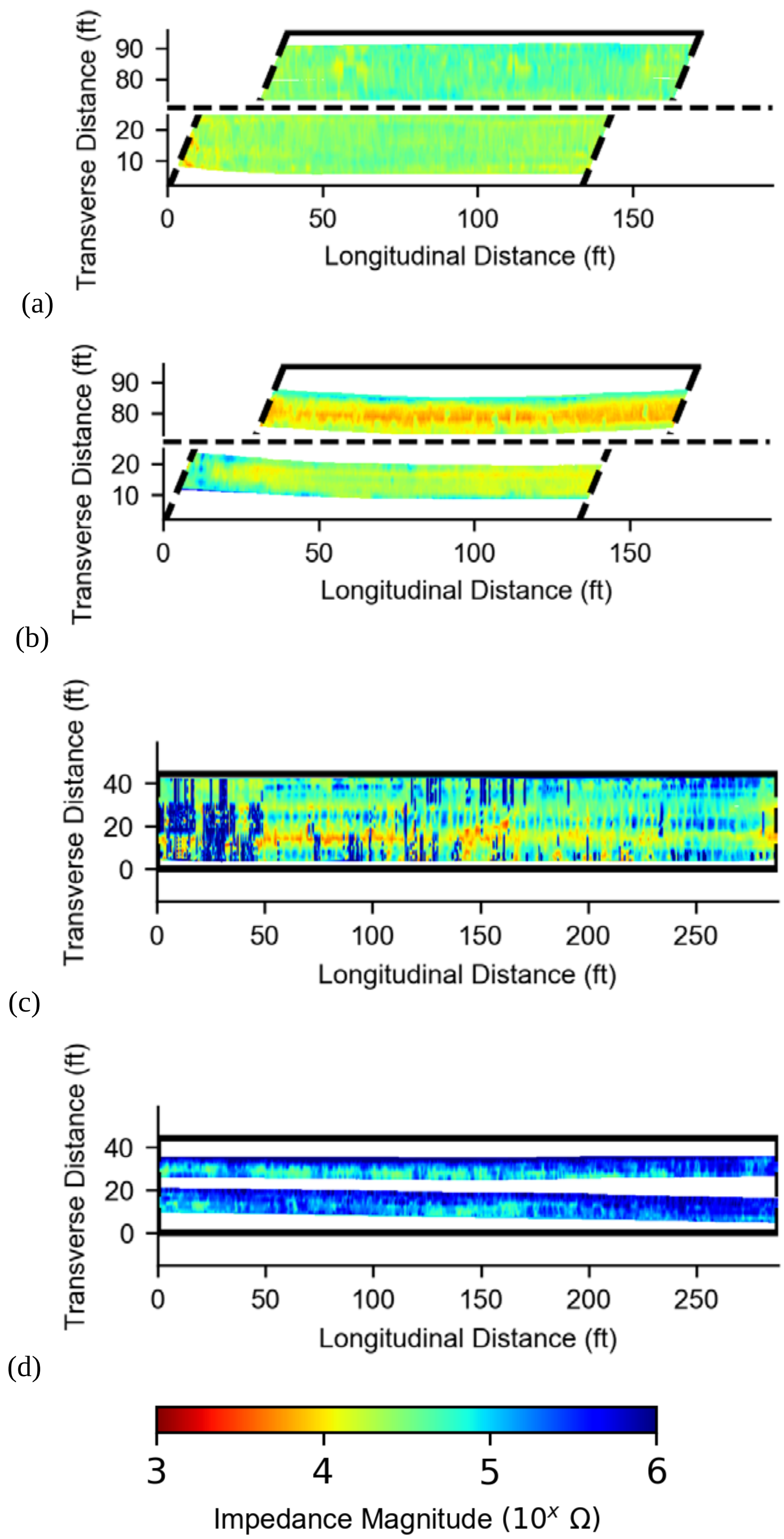


FIGURE 26 (a) VEI map of bridge deck 1 before overlay placement. (b) VEI map of bridge deck 1 approximately two years after overlay placement. (c) VEI map of bridge deck 2 before overlay placement. (d) VEI map of bridge deck 2 approximately two years after overlay placement.

Stage II Improvements to the VEI Scanner

Significant improvements were made to the VEI scanner during Stage II. Two removable wedge plates were added to the apparatus as shown in Figure 27. The purpose of these wedge plates was to improve mobility when the apparatus was winched up. Prior to the addition of these plates, when the fully extended apparatus was winched up, the two front tires of the apparatus remained on the ground and hindered turning of the apparatus with the tow vehicle, which was necessary when turning around for scanning of a bridge deck that carried traffic in two directions. The two added wedges ensure that the two front tires of the apparatus are lifted off the ground. Specifically, as the apparatus is lifted, the wedges stop rotational movement of the lower set of hinges earlier than when the wedges are not present. Stopping rotation of those hinges then permits the second set of hinges to engage and rotate earlier in the winching process. The simple addition of the wedges greatly increased the usability of the apparatus because it significantly reduced the turning radius of the tow vehicle when the VEI scanner was not in a fully stowed position.

The next improvement made to the apparatus was the addition of a third 5-gpm pump in parallel with the existing two pumps as part of the water sprinkler system. The addition of this pump increased the flow rate of the overall system by approximately 50%. The new flow rate is approximately 15 gpm, which equates to approximately 0.007 gallons per square foot when traveling at 2 mph. This water flow rate now can exceed the recommended minimum flow rate of 0.005 gallons per square foot specified. A water flow meter with 1.5% accuracy from 0.22 to 22 gpm was also added to the outlet pipe of the main water tank, as shown in Figure 28. This meter permitted more accurate calculations of the volume of water being sprayed onto the bridge deck in a given test and increased understanding of the effects of water on the overall impedance measurements. This meter has a mechanical readout but can be instrumented in the future for digital tracking of water usage dynamically during scanning.

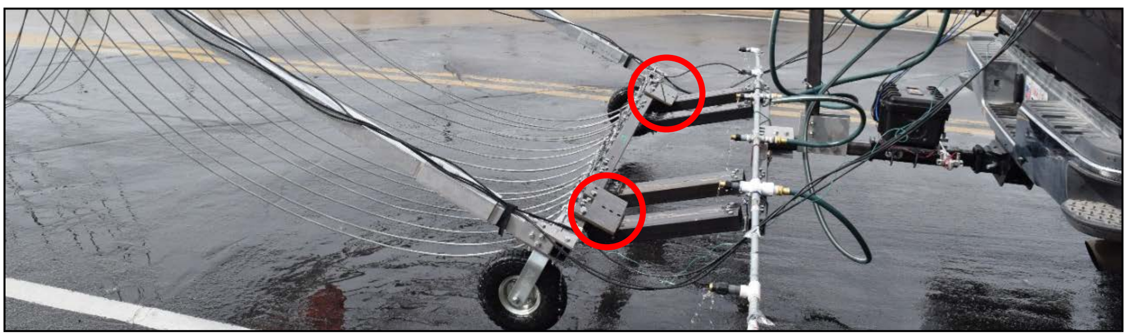


FIGURE 27 Photograph of the new wedge plates (circled in red) installed to improve the lifting action of the VEI scanner by raising the two front wheels off the ground and thereby enhancing the mobility of the system.

FIGURE 28 Photograph of the new inline water meter used to log water flow during VEI scanning.

Bridge Deck Scanning in Nebraska

In collaboration with researchers at the University of Nebraska-Lincoln, a bridge scanning tour was arranged in Nebraska in August 2018 under the auspices of the Nebraska Department of Transportation. Three bridge decks, one bare, one with a low-slump concrete overlay, and one with an asphalt overlay, were selected for scanning in eastern Nebraska. Nebraska Bridge Deck 1 (Figure 29 (top)) was built in 1995. It is a three-span cast-in-place concrete deck with a monolithic concrete surface and epoxy-coated reinforcing steel and was supported by continuous steel girders. The bridge deck is 293 ft long and 46.3 ft wide (out to out) and is located on a rural minor arterial road with an estimated average daily traffic (ADT) of 3730. At the time of testing, the deck carried a northbound and a southbound lane with approximately 8-ft-wide shoulders on each side. To evaluate Nebraska Bridge Deck 1 with the VEI scanner, both the southbound lane and shoulder were scanned twice. During these four passes, 12.5, 12.3, 18.9, and 15.6 gallons of water were applied to the deck surface. These amounts corresponded to approximately 0.003 to 0.005 gallons per square foot, which was consistent with the water usage specifications developed earlier in this research. (During the second pass along the southbound shoulder, one of the probe cables was accidently cut when the apparatus was winched up, which resulted in a loss of data for that probe only; interpolation between adjacent probes was used to estimate values for the missing data.) Immediately after impedance scanning was performed, preliminary impedance maps were generated to enable identification of a low-impedance location and a high-impedance location on the deck for chloride concentration testing. At each location, two samples were obtained using a rotary hammer. The first sample represented the depth interval from 0 to 1 in., while the second sample represented the depth interval from 1 to 2 in. After removal, the samples were returned to Brigham Young University for laboratory analysis.

FIGURE 29 (Top) photograph of Nebraska Bridge Deck 1 on which scanning took place in the southbound lane and shoulder and (bottom) photograph of a chloride concentration sampling location that corresponded to a construction joint characterized by lower impedance values.

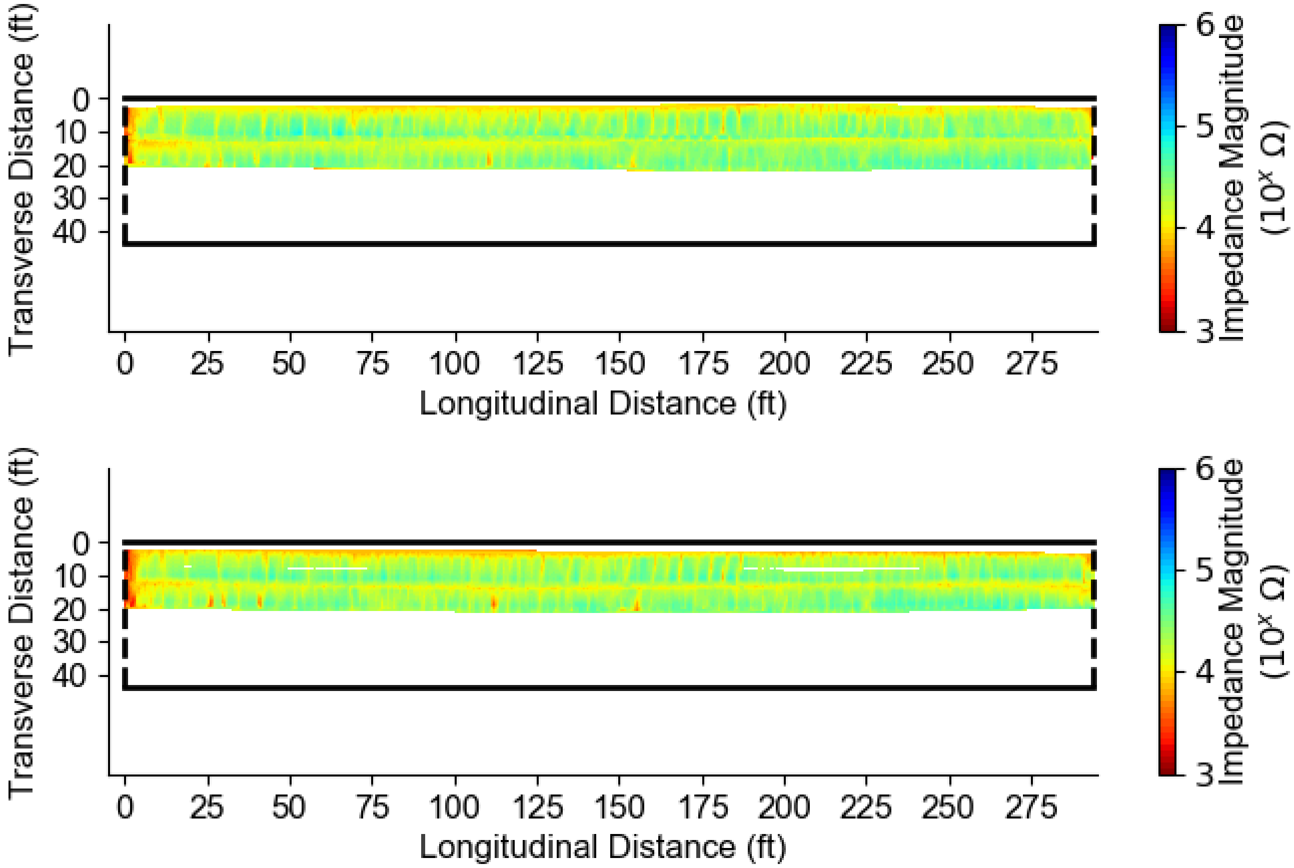


FIGURE 30 (Top) VEI map generated from the first passes and (bottom) VEI map generated from the second passes.

The results of the two passes of VEI scanning on Nebraska Bridge Deck 1 are shown in Figure 31. A prominent feature of the impedance maps is a long line of low impedance running the length of the bridge approximately 12 ft from the parapet wall. Visual inspection indicated that this line corresponds to a construction joint running the length of the bridge, a portion of which is shown in Figure 29 (bottom). Other distinctive features prominently shown on the maps of Nebraska Bridge Deck 1 are multiple transverse lines, spaced every few feet along almost the entire length of the bridge. These features correlated well with observed transverse shrinkage cracks that occurred at fairly consistent intervals along the length of the deck. From the data shown in Figure 30, soaking during subsequent scanning passes did not appear to significantly change the results between passes. For this bridge deck, the low-impedance chloride concentration sampling location was positioned at (212 ft, 15 ft), while the high-impedance chloride concentration sampling location was positioned at (162 ft, 9 ft). The results of the chloride concentration testing are shown in Table 1.

Nebraska Bridge Deck 2 was built in 1965 and was reconstructed in 1978. Shown in Figure 31, it is a three-span cast-in-place concrete deck with a low-slump concrete overlay and is supported by continuous steel girders. The bridge deck is 180 ft long and 39.6 ft wide (out to out). The bridge is located on a principal road with an estimated ADT of 12,415. At the time of testing, the deck carried two lanes of northbound traffic with an approximately 10-ft-wide shoulder on the right and a 5-ft-wide shoulder on the left. To evaluate Nebraska Bridge Deck 2 with the VEI scanner, both the right lane and right shoulder were scanned three times. The third pass of the shoulder was deliberately performed at about 10 mph, which is approximately triple the speed of all other passes shown. During the six passes across the bridge deck, 12.0, 10.8, 11.6, 10.2, 8.8, and 3.8 gallons of water were applied to the deck surface. These amounts corresponded to approximately 0.004 to 0.005 gallons per square foot for the first five passes, which was again consistent with the water usage specification developed earlier in this research. For the last, fast pass, which was performed immediately following the earlier passes, the amount of applied water corresponded to about 0.002 gallons per square foot; this last pass was benefited by moisture already present on the deck surface. Immediately after impedance scanning was performed, preliminary impedance maps were generated to enable identification of a low-impedance location and a high-impedance location on the deck for chloride concentration testing, which was performed using the same procedures applied to Nebraska Bridge Deck 1.

The results of VEI scanning of Nebraska Bridge Deck 2 are shown in Figure 32. Like Nebraska Bridge Deck 1, Nebraska Bridge Deck 2 had consistent transverse lines characterized by low impedance across the bridge deck; however, the lines are less frequent and less distinct than those observed on Nebraska Bridge Deck 1. Nebraska Bridge Deck 2 also had a longitudinal line characterized by low impedance approximately 10 ft from the parapet wall. This line corresponded to a construction joint present on the bridge directly beneath the shoulder line. The other main feature of the impedance map for Nebraska Bridge Deck 2 is the occurrence of multiple large areas of low impedance near both ends of the bridge deck. Although these areas exhibited no visually apparent defects, a chain drag indicated that these locations were delaminated. Lastly, areas along the shoulders of the deck in which debris had accumulated also correlated spatially with some of the low-impedance areas on the map; these areas may have been more susceptible to salt accumulation during winter. The impedance values changed slightly between the first and second passes; however, the impedance values did not change significantly between the second and third passes. The impedance values for the third pass, which was performed at higher speed, had different magnitudes than the earlier passes, as shown in Figure 32(d), but retained high spatial

FIGURE 31 Photograph of Nebraska Bridge Deck 2 prior to scanning.

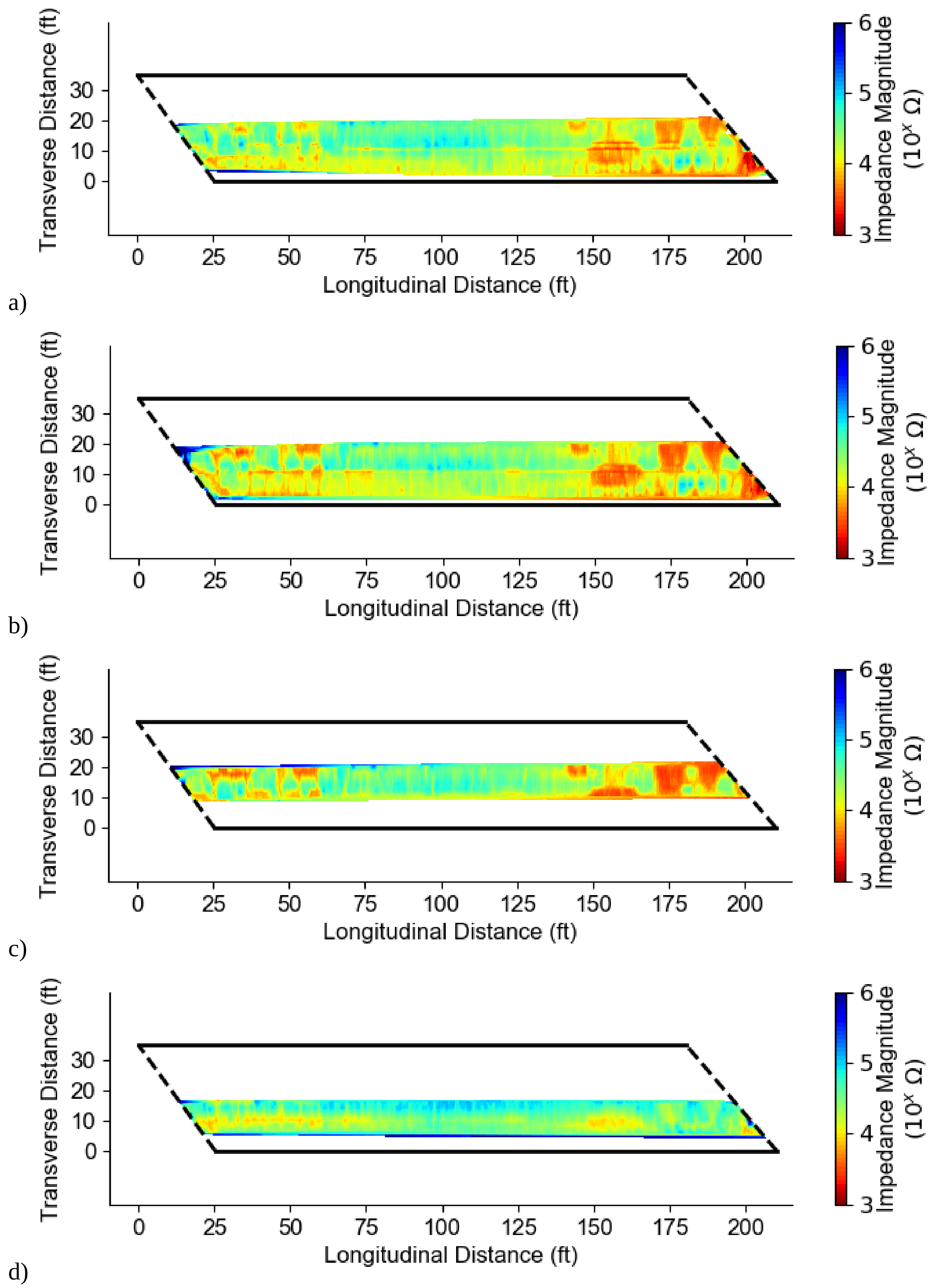


FIGURE 32 (a) VEI map generated from the first pass, (b) VEI map generated from the second pass, (c) VEI map of the right lane generated from the third pass, and (d) VEI map of the right shoulder generated from the third pass at higher speed.

correlation with those passes. The sharpness of the contours in this map was also reduced, which may be a result of data blurring during data acquisition. These data suggest that the speed of impedance testing may have a greater effect on the results than the soaking time. More data will be needed to explore the effect of data acquisition speed, but, for routine data acquisition using the current apparatus, a scanning speed of 2 to 3 mph is recommended as an upper limit. For this bridge deck, the low-impedance chloride concentration sampling location was positioned at (176 ft, 16 ft), while the high-impedance chloride concentration sampling location was positioned at (102 ft, 12 ft). The results of the chloride concentration testing are shown in Table 1.

Nebraska Bridge Deck 3, shown in Figure 33, was built in 1958. It is a three-span cast-in-place concrete deck with an asphalt overlay and is supported by continuous concrete girders. The bridge deck is 54 ft long and 33 ft wide (out to out) and is located on a rural minor arterial road with an estimated ADT of 1950. At the time of testing, the deck carried one lane of northbound traffic and one lane of southbound traffic with minimal shoulders. To evaluate Nebraska Bridge Deck 3 with the VEI scanner, both the northbound and southbound lanes were scanned three times. During the six passes across the bridge deck, 14.2, 8.1, 6.7, 14.1, 9.8, and 11.5 gallons of water were applied to the deck surface. These amounts corresponded to approximately 0.008 to 0.017 gallons per square foot for the six passes, which was above the recommended water usage specification. The extra water was deliberately applied, however, to ensure that the asphalt overlay was sufficiently soaked for testing. Immediately after impedance scanning was performed, preliminary impedance maps were generated to enable identification of a low-impedance location and a high-impedance location on the deck for chloride concentration testing, which was performed using the same procedures applied to Nebraska Bridge Decks 1 and 2.

FIGURE 33 Photograph of Nebraska Bridge Deck 3.

The results of VEI scanning of Nebraska Bridge Deck 3 are shown in Figure 34. Noticeably, there are lower impedance values along both edges of the bridge and down the center. The lower impedance values along the edge of the bridge are possibly the result of snow storage and salt accumulation during winter. The lower impedance values down the middle are likely caused by a cold joint during the asphalt placement process. Another prominent feature shown in this bridge map is the slightly lower impedance line that runs diagonally from location (20 ft, 20 ft) to (33 ft, 3 ft). Because the impedance data were able to be quickly processed on site, a preliminary VEI map was obtained after the first pass. To investigate this diagonal line, the bridge engineers participating in the work inspected the bottom of the bridge deck. They determined that the line coincided with a visible crack in the asphalt overlay that was caused from an underlying deck construction joint, which exhibited efflorescence on the underside of the bridge. The impedance map revealed this defect that otherwise would not have been observed. Finally, there is a line of lower impedance visible in the upper lane of the map. Although there was no physical evidence of defects along the line, it coincided with a wheel path, where deterioration is probably more accelerated compared to the rest of the bridge deck. For this bridge deck, the low-impedance chloride concentration sampling location was positioned at (43 ft, 11 ft), while the high-impedance chloride concentration sampling location was positioned at (25 ft, 9 ft). The results of the chloride concentration testing are shown in Table 1.

For each of the three Nebraska bridge decks, the chloride concentrations measured at the high-impedance location were lower than those measured at the low-impedance location, as expected. VEI measurements were shown to be sensitive to both visible and non-visible defects, and their utility was demonstrated during scanning of especially the asphalt-overlaid deck, for which other evaluation techniques were not successful. A comparison of the VEI data obtained from all three bridges in Nebraska suggests that asphalt overlays appear to provide significant resistance to chloride ingress. This protection, for which a longer soaking time is needed for water to penetrate the asphalt and percolate through defects in an underlying membrane, is about an order of magnitude larger than that associated with bare decks.

TABLE 1 Chloride Concentration Test Results

Bridge Deck	Longitudinal Distance (ft)	Transverse Distance (ft)	Average Depth (in.)	Chloride Concentration (lb Cl^-/yd^3 Concrete)	Impedance Magnitude (Ω)
1 Bare	162	9	0.5	17.4	32,000
			1.5	2.0	
	212	15	0.5	20.0	10,000
			1.5	10.6	
2 Concrete Overlay	102	12	0.5	4.0	79,000
			1.5	1.1	
	176	15.5	0.5	13.3	2,500
			1.5	9.0	
3 Asphalt Overlay	24.5	8.5	0.5	10.4	630,000
			1.5	8.6	
	42.5	10.5	0.5	13.9	6,300
			1.5	13.4	

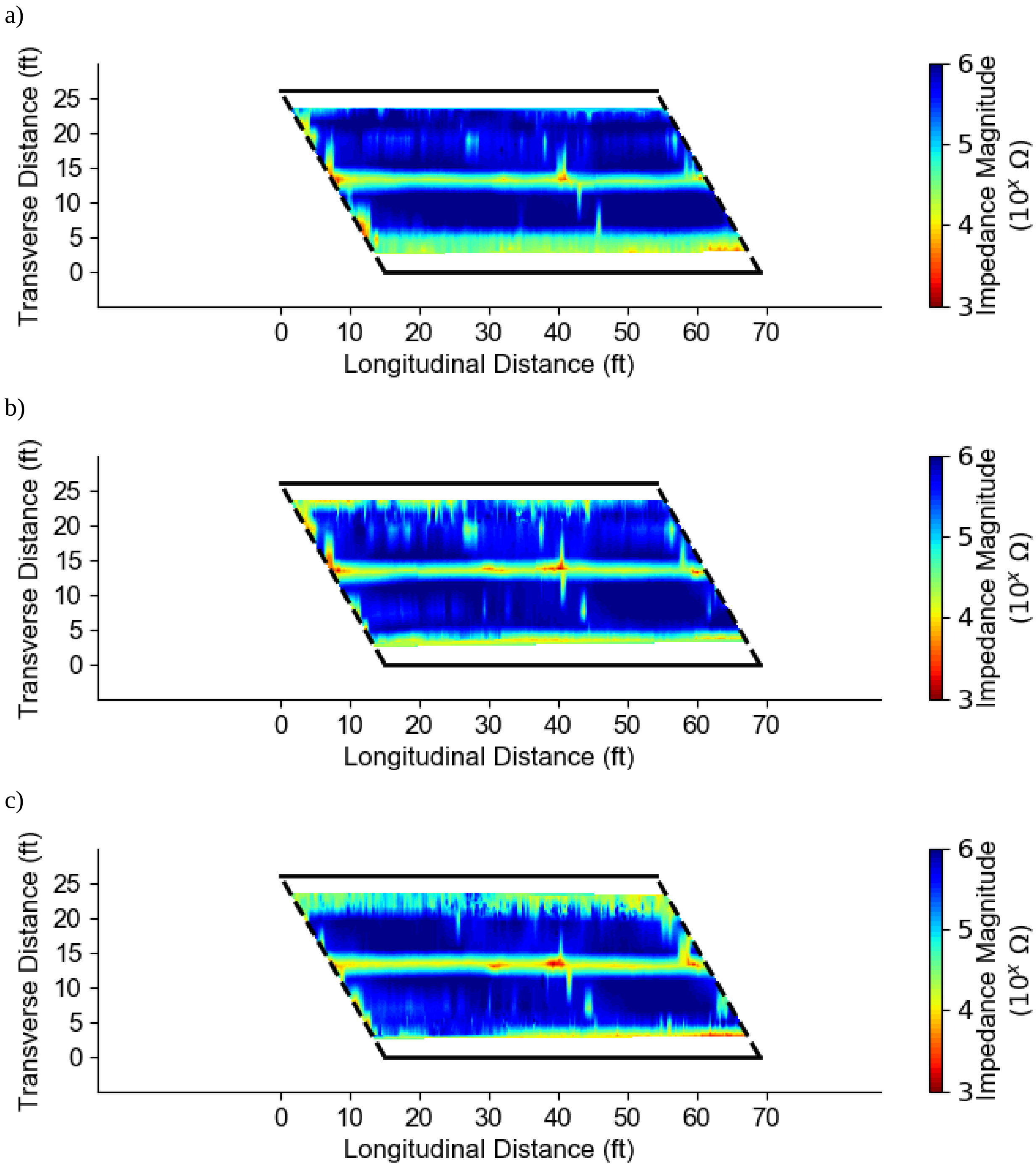


FIGURE 34 (a) VEI map generated from the first pass, (b) VEI map generated from the second pass, and (c) VEI map generated from the third pass.

Bridge Deck Scanning in Utah and Comparison with Crack Survey

The final task performed in Stage II was scanning a bridge deck in northern Utah. Shown in Figure 35, Utah Bridge Deck 1 was built in 1970. It is a two-span cast-in-place concrete deck with a monolithic concrete surface and is supported by continuous concrete girders. The bridge deck is 256 ft long and 45 ft wide (out to out). The bridge is on an urban local road with an estimated ADT of 5,000. The bridge has a 12-ft-wide northbound lane and a 14-ft-wide southbound lane with an approximately 3.3-ft-wide northbound shoulder and a 2.8-ft-wide southbound shoulder. This bridge also has 6-ft-wide pedestrian walkways on both sides of the bridge. Testing occurred after a week of heavy rain, so the bridge deck had been exposed to high levels of moisture that enabled excellent electrical coupling of the impedance probes to the deck surface. During VEI scanning, both lanes were alternately scanned six times, with each pass having a slightly different transverse offset. Each pass was performed at the recommended speed of approximately 1 to 3 mph, with the exception of the sixth pass that was performed at a higher speed of approximately 8 mph in both lanes. One of the probes on each pass measured lower-than-expected impedance values, which were subsequently determined to be invalid and discarded; interpolated values based on valid measurements obtained using adjacent probes were used instead. During the six passes in the northbound direction, approximately 16.6, 13.0, 20.6, 13.5, 13.4, and 5.6 gallons of water were applied to the deck surface. During the six passes in the southbound direction, approximately 11.9, 14.1, 15.0, 12.7, 12.2, and 4.7 gallons of water were applied to the deck surface. These amounts corresponded to approximately 0.004 to 0.005 gallons per square foot for the five passes, which was consistent with the water usage specification developed earlier in this research. For the last, fast pass, the amount corresponded to about 0.002 gallons per square foot. Noticeably, the soaking time for the fast pass was also reduced. One year prior to testing, this bridge deck had been extensively inspected using chain dragging to develop a delamination map. In addition, a detailed crack map was also prepared from a careful visual inspection. The crack and delamination map is shown in Figure 36(a).

The results of impedance scanning are also shown in Figure 36. Comparison of the impedance maps with the delamination and cracking maps clearly shows a strong correlation (some differences may be attributable to changes that occurred to the bridge deck during the 1-year period between the measurements). Comparing the results of a lower-speed pass with those of a higher-speed pass is also interesting. As evidenced in Figure 36, scanning at a higher speed appears to reduce the sharpness of the contours in the resulting map. As mentioned previously, this effect may be a result of data blurring during data acquisition and will be investigated in further research.

FIGURE 35 Photograph of VEI scanning on Utah Bridge Deck 1.

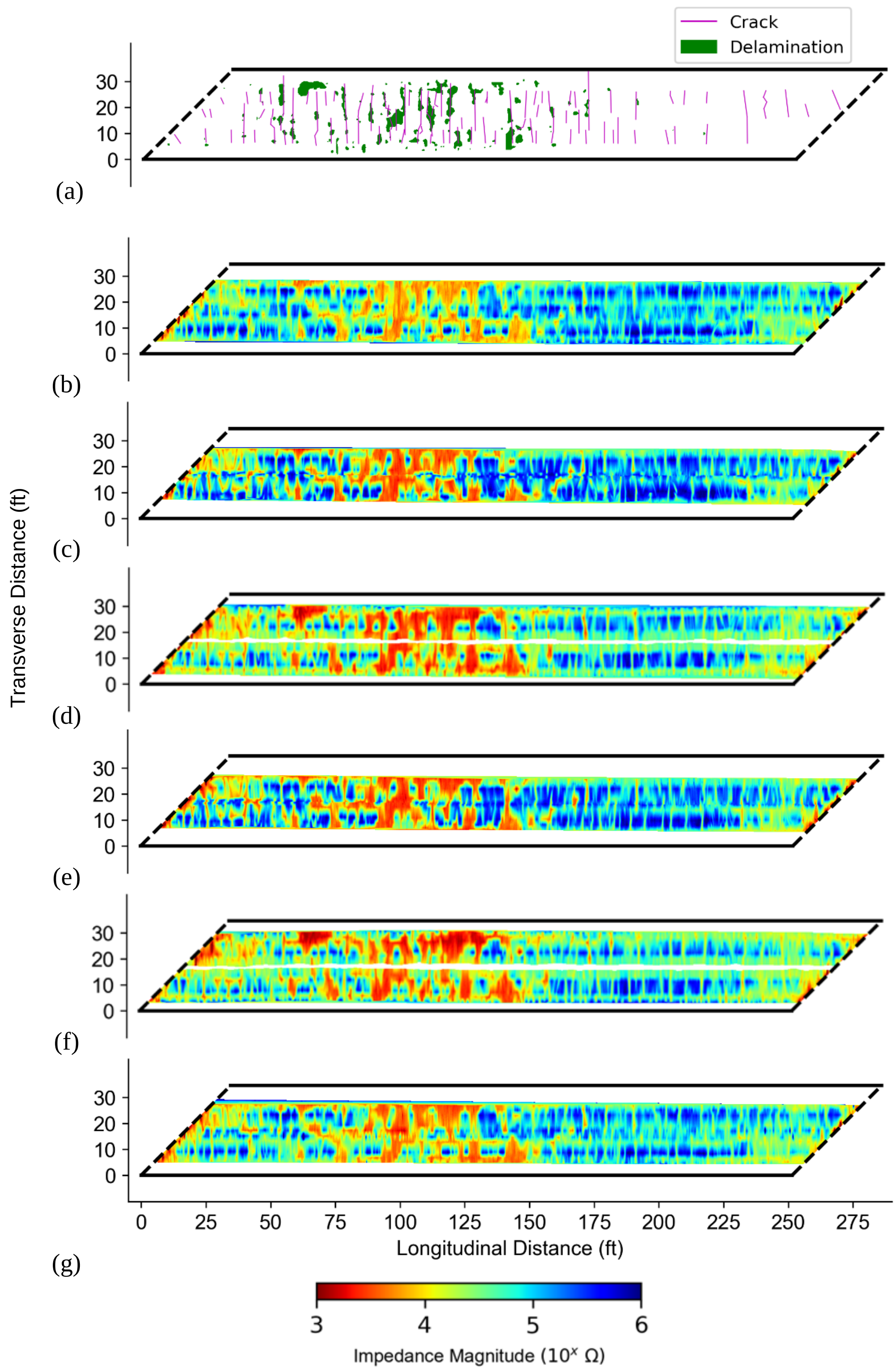


FIGURE 36 (a) Crack and delamination survey map for Utah Bridge Deck 1. (b)-(f) VEI maps obtained at a speed of approximately 3 mph and (g) VEI map obtained at higher speed.

The main results of Stage II were (1) refinement of the VEI scanner and specification of its operation in the field and (2) refinement of interpretation of results from VEI scanning. Field testing was performed multiple times under very different conditions in two different states. These results from Stage II give high confidence that the VEI scanner can be successfully and consistently deployed in the field and that VEI maps can complement other data about bridge decks to guide bridge managers in making improved decisions about deck rehabilitation strategies. The developments in Stage II also provide additional refinements that will allow the scanner to be deployed commercially after this project is complete.

OBSERVATIONS

The availability of water is a definite consideration for VEI testing, especially when the tests will be executed in remote areas where water may not be readily accessible. Careful planning may be required in some areas to ensure that water can be obtained for testing. For most of the bridge deck scanning in Utah, the water was obtained from university laboratories before field work commenced. At other times, hotels or fuel stations allowed the use of water from exterior faucets. In Nebraska, Department of Transportation personnel provided access to water at one of their facilities. In all cases, the use of large, 2-in.-diameter water hoses is desirable to be able to more rapidly fill the water containers. The quality of water does not seem to be a significant issue because the electrical conductivity of water is so much higher than that of concrete or typical deck overlay materials, regardless of any solutes dissolved in the water; nonetheless, the use of potable water is recommended for consistency with the VEI scanning procedures utilized in the development of this technology.

Even in the parallel arrangement of the probes on the surface, in which the probes operate at different frequencies, some uncertainty in the measurement system is possible. Because there are many parallel low-impedance signal sources in the system, the sources create virtual grounds for each of the other signals, effectively creating another low-resistance path that is in parallel to the path from the LAE. This alternative path is not a primary reason for errors in the measurements, but it is present nonetheless. The effect of this alternative path could be exacerbated if too much water (more than a thin film) is placed on the bridge deck surface because the electrical coupling between the probes would be more significant in that case.

Developing circuitry that maintains a constant voltage across the material to be interrogated may also be desirable. To achieve rapid VEI measurements without switching different measurement resistors into and out of the measurement circuit (as other auto-ranging equipment often does), the signal passes through the current measurement resistor before being transmitted to the measurement probe. Therefore, when the resistance of the bridge deck is very low, the signal amplitude across the bridge deck is lower than when the bridge deck resistance is very high. While this does not appear to be a complicating factor in the overall measurement, it does mean that, if the signals were all driven at the same frequency, the guard ring amplitudes would be different from each other, which may cause some additional horizontal currents across the probe areas. Again, the deployed solution does not appear to be greatly affected by these effects, but these are considerations that might be examined in future versions of the VEI scanner.

In this research, most VEI measurements obtained from field testing ranged from 10^3 Ω to 10^6 Ω. VEI measurements smaller than 10^4 Ω were generally associated with areas of concerns and were more likely to exhibit delamination or other major deterioration. VEI measurements greater than 10^5 Ω were generally associated with areas in good condition, without apparent problems. VEI measurements between 10^4 and 10^5 Ω were generally associated with areas that exhibited minor deterioration, such as cracking, that may lead to major deterioration in the future.

PLANS FOR IMPLEMENTATION

Multiple aspects of implementation speak favorably for this project, including collaboration with end users, intellectual property protection, case study publications, and a clear path to commercialization through an entity that has already licensed bridge inspection technology from our research group. This project benefited from extensive collaboration with the Utah Department of Transportation and the Nebraska Department of Transportation. These collaborations resulted in access to multiple bridge decks for field testing and also ensured that the data generated by VEI scanning would be used to inform actual potential users of the technology. In particular, as the Nebraska Department of Transportation is more frequently specifying asphalt overlays for protection of concrete bridge decks, the VEI technology was particularly interesting to them as an additional inspection method. By working directly with representatives from different departments of transportation, we also received valuable feedback about the use and interpretability of the data obtained from VEI scanning.

Beyond the unique capability of VEI scanning for evaluating asphalt overlays on concrete bridge decks, the potential for VEI scanning without stationary traffic control is also attractive. Instead, the use of rolling traffic control may be possible in some cases. In summary, the bridge managers with whom we have worked have been uniformly impressed with the data we have obtained from our field experiments.

The following three patents have been issued to protect the intellectual technology associated with VEI scanning:

U.S. Patent 9,816,978 Apparatus for analysis of concrete including a reinforcing bar

U.S. Patent 9,909,974 Data acquisition system with rotating probe members and ground reference electrode

U.S. Patent 10,082,492 Flexible elements for probes and guard rings

Additional patent applications have also been filed to protect other critical aspects of this technology. In addition to the intellectual property protection offered by patents, the following four peer-reviewed papers have been published during the course of this project to give further credibility and expanded information about the VEI scanning technology:

J. Barton, J. Baxter, W. S. Guthrie, and B. A. Mazzeo. Vertical electrical impedance scanner for non-destructive concrete bridge deck assessment without a direct rebar connection. *Materials Evaluation*, in press.

J. Barton, J. Baxter, W. S. Guthrie, and B. A. Mazzeo. Large-area electrode design for vertical electrical impedance scanning of concrete bridge decks. *Review of Scientific Instruments* **90**, 025101 (2019).

J. S. Baxter, W. S. Guthrie, T. Waters, J. D. Barton, and B. A. Mazzeo. Vertical electrical impedance evaluation of asphalt overlays on concrete bridge decks. *44th Annual Review of Progress in Quantitative Nondestructive Evaluation, AIP Conference Proceedings* **1949**, 030011 (2018).

W. S. Guthrie, J. Baxter, B. A. Mazzeo. Vertical impedance testing of a concrete bridge deck using a rolling probe. *NDT&E International* **95**, 65-71 (2018).

These papers describe the use of this technology and explain specific elements of the design. Aspects of this work have also been presented at multiple professional conferences. Additional publications and presentations are planned, which will further support the implementation of this technology.

A path for commercialization of this technology has already been identified. An advanced acoustic sounding apparatus and method was developed by our research group and subsequently licensed to Advanced Bridge Inspections, LLC. Based in Utah, this company has deployed that technology in the field on projects from California to New York. Furthermore, the company is familiar with the development platforms that we have used in that system, which are similar in many respects to those used in our development of the VEI scanner, and students who previously worked in our research group on the development of these technologies have accepted positions at this company following graduation. To further expand their testing services, the company has also licensed the VEI scanning technology that was the subject of this research and will be able to offer VEI scanning services commercially.

As part of this research, extensive development of localization and mapping software was needed to enable implementation of the VEI technology. Continuing advances in localization software toward the commercialization of self-driving vehicles are expected to enable simpler VEI scanning through the future integration of VEI measurements with localization data collected automatically by on-board vehicle systems.

To ensure that VEI data are collected properly and are useful for bridge deck management, specific training should be obtained by those who are collecting and interpreting the data. The following objectives are proposed for such training:

1) An understanding that large impedances will dominate the measurement of a set of impedances in series.
2) An understanding of factors that affect impedance, including material properties and different coatings such as asphalt membranes and epoxy on steel reinforcement.
3) An understanding of overall impedance characteristics of bare decks and decks with different types of overlays.
4) An understanding of the influence of features such as joints, cracks, and delaminations, which can have high electrical conductivity, on VEI measurements.
5) An understanding of the necessity of a water layer to form a conductive film through which electrical measurements are obtained and the ability to assess the adequacy of the water film in the field.
6) An understanding of the use of repeated scans to ensure adequate VEI measurement stability.
7) An understanding of how localization is performed and how to ensure that appropriate procedures are in place to establish the relative positions of GPS antennae, LiDAR units, and measurement probes to compensate for varying scanner geometry, especially when different towing vehicles are used.
8) An understanding of how VEI data can be used to guide destructive sampling techniques, such as core extraction, to aid in overall bridge deck evaluation.

These plans will help ensure that the VEI scanning technology developed in this research will be successfully transferred from the university to a commercial entity and made available to the transportation community.

CONCLUSIONS

Chloride-induced corrosion of steel reinforcement in concrete bridge decks is a major concern for bridge owners and managers. Bridge decks in marine areas and cold regions experience rapid and widespread steel corrosion due to the presence of elevated concentrations of salts that are either naturally present in the marine environment or deliberately applied in cold regions for safety. Over time, salts can diffuse through the concrete cover, after passing through any overlays that may be applied to the deck surface, and initiate corrosion of the steel reinforcement. Because early intervention, before concrete cracking has occurred, is the most cost-efficient bridge deck management approach, a device for measuring the quality of protection offered to the steel reinforcement on bridge decks was needed.

To address this need, a multi-channel VEI scanner incorporating an LAE was developed in this research. This hitch-mounted scanner can be easily transported to bridge decks and quickly deployed on site with minimal or no stationary traffic control. The LAE permits VEI scanning without the need for a direct electrical connection to the steel reinforcement. Studies indicate that low VEI measurements, particularly those below 10^4 Ω, are correlated with compromised cover protection as evidenced by higher chloride concentrations within the concrete compared to areas with higher VEI.

Cost-effective, nondestructive evaluation of concrete bridge deck cover protection is now available with this VEI scanning apparatus. The scanner can be used effectively on bare and overlaid concrete bridge decks, enabling broad application of the technology. For project-level bridge deck investigations, this device permits mapping of spatial variations in VEI to effectively guide additional, more localized testing, such as chloride concentration determinations. In conjunction with other such tests, the VEI scanner provides valuable data that support decision-making by bridge managers responsible for appropriately selecting among preservation, rehabilitation, and replacement options available within their bridge management programs.

With support from the Utah Department of Transportation and the Nebraska Department of Transportation, extensive testing of the VEI scanner was performed on multiple bare and overlaid concrete bridge decks in Utah and Nebraska in 2018. Field deployment demonstrated that multi-channel measurements could be performed in parallel and that implementation of the LAE successfully eliminated the need for a direct electrical connection to the steel reinforcement. VEI scanning at rates exceeding 1500 ft^2/minute was achieved in this project.

This technology is licensed to Advanced Bridge Inspections, LLC, based in Pleasant Grove, Utah, for commercial evaluation of concrete bridge decks.

REFERENCES

[1] M. C. Brown, J. P. Gomez, M. L. Hammer, and J. M. Hooks, "Long-term bridge performance high priority bridge performance issues," FHWA-HRT-14-052, 2014.

[2] B. A. Mazzeo, J. Larsen, J. McElderry, and W. S. Guthrie, "Rapid Multichannel Impact-Echo Scanning of Concrete Bridge Decks from a Continuously Moving Platform," *AIP Conference Proceedings*, vol. 1806, 080003, 2017.

[3] B. A. Mazzeo and W. S. Guthrie, "Algorithms for highway-speed acoustic impact-echo evaluation of concrete bridge decks," in *AIP Conference Proceedings*, vol. 1949, 030010, 2018.

[4] J. Barton, J. Baxter, W. S. Guthrie, and B. A. Mazzeo, "Large-area electrode design for vertical electrical impedance scanning of concrete bridge decks," *Review of Scientific Instruments*, vol. 90, 025101, 2019.

[5] N. C. Barrus, "Sensitivity of resistivity measurements on concrete bridge decks to operator-controlled and concrete material variables," MS, Civil and Environmental Engineering, Brigham Young University, Provo, UT, 2012.

[6] P. D. Bartholomew, W. S. Guthrie, and B. A. Mazzeo, "Vertical impedance measurements on concrete bridge decks for assessing susceptibility of reinforcing steel to corrosion," *Review of Scientific Instruments*, vol. 83, 085104, 2012.

[7] H. M. Argyle, "Sensitivity of electrochemical impedance spectroscopy measurements to concrete bridge deck properties," MS, Civil and Environmental Engineering, Brigham Young University, Provo, UT, 2014.

[8] W. S. Guthrie and B. A. Mazzeo, "Vertical Impedance Testing for Assessing Protection from Chloride-Based Deicing Salts Provided by an Asphalt Overlay System on a Concrete Bridge Deck," in *Cold Regions Engineering 2015*, W. S. Guthrie, Ed., 2015, pp. 358-369.

Program Steering Committee:
NCHRP IDEA Program Committees

May 2019

Project NCHRP-202
Start Date: April 2017
Completion Date: May 2019

Product Category:
Highway IDEA Program

Principal Investigators:
Professor Brian Mazzeo
Brigham Young University
bmazzeo@byu.edu

Professor W. Spencer Guthrie
Brigham Young University
guthrie@byu.edu

NCHRP NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

RESEARCH RESULTS

Vertical Electrical Impedance Scanner for Bridge Decks

A new, rapid scanner was developed to evaluate concrete cover protection offered to steel reinforcement

WHAT WAS THE NEED?

Chloride-induced corrosion of steel reinforcement in concrete bridge decks is a major concern for bridge owners and managers. Bridge decks in marine areas and cold regions experience rapid and widespread steel corrosion due to the presence of elevated concentrations of salts that are either naturally present in the marine environment or deliberately applied in cold regions for safety. Over time, salts can diffuse through the concrete cover, after passing through any overlays that may be applied to the deck surface, and initiate corrosion of the steel reinforcement. Because early intervention, before concrete cracking has occurred, is the most cost-efficient bridge deck management approach, a device for measuring the quality of protection offered to the steel reinforcement was needed.

WHAT WAS OUR GOAL?

The research objective was to develop a multi-channel vertical electrical impedance scanner with a large-area electrode to quantify the cover protection offered to reinforcing steel in bridge decks without a direct rebar connection.

WHAT DID WE DO?

A new vertical electrical impedance scanner was developed that could be rapidly deployed in the field. New electronics were designed to perform the impedance measurements and to perform localization so that mapping of the impedance data could be automatically performed. The large-area electrode developed for this impedance system permitted data collection without a direct electrical connection to the steel reinforcement.

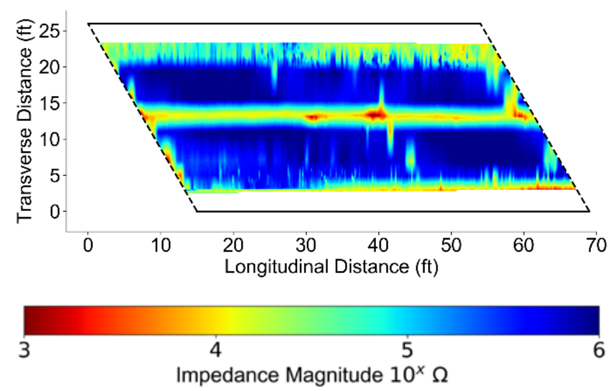
With support from the Utah Department of Transportation and the Nebraska Department of Transportation, extensive testing of the vertical electrical impedance scanner was performed on multiple bare and overlaid concrete bridge decks in Utah and Nebraska.

WHAT WAS THE OUTCOME?

Field deployment demonstrated that multi-channel measurements could be performed in parallel and that implementation of the large-area electrode successfully eliminated the need for a direct electrical connection to the steel reinforcement. Vertical electrical impedance scanning at rates exceeding 1500 ft^2/minute was achieved in this project.

WHAT IS THE BENEFIT?

Cost-effective, nondestructive evaluation of concrete bridge deck cover protection is now available with this vertical electrical impedance scanning apparatus. The scanner can be used effectively on bare and overlaid concrete bridge decks, enabling broad application of the technology. For project-level bridge deck investigations, this device permits mapping of spatial variations in VEI to effectively guide additional, more localized testing, such as chloride concentration determinations. In conjunction with other such tests, the VEI scanner provides valuable data that support decision-making by bridge managers responsible for appropriately selecting among preservation, rehabilitation, and replacement options available within their bridge management programs.



Map of vertical electrical impedance data on an asphalt-overlaid concrete bridge deck, with areas of compromised cover protection indicated.

LEARN MORE

To view the complete report:
http://www.trb.org/IDEAProgram/NCHRPHighwayIDEACompletedProjects.aspx

For more information:
bmazzeo@byu.edu
guthrie@byu.edu