Performance of Concrete Bridge Decks of Similar Construction and Environment, but Different Traffic Loads

Hoda Azari, Nenad Gucunski, Jinyoung Kim, and Kien Dinh

Maintenance, rehabilitation, and replacement of reinforced concrete decks are the largest bridge component expenditures for most transportation agencies. Therefore, concrete bridge deck performance was identified as one of the key bridge performance issues in the Federal Highway Administration's Long-Term Bridge Performance Program. To improve knowledge of bridge deck performance, high-quality quantitative performance data should be collected periodically through the use of complementary nondestructive evaluation (NDE) technologies, such as impact echo, ground penetrating radar, half-cell potential, ultrasonic surface waves, and electrical resistivity. This paper presents the condition change of a bridge deck in Virginia over a period of six years. The assessment covered corrosive environment and corrosion processes, concrete degradation, and deck delamination. Deterioration progression from periodic NDE surveys is illustrated qualitatively by condition maps and quantitatively by condition assessment numbers. The results demonstrate the ability of NDE technologies to capture and quantify the progression of deterioration. Strong agreement between different NDE technology results improves the confidence level of the condition assessment of the deck. The study also evaluated the similarities in performance of bridge decks of comparable age, similar construction, and similar environment, with different traffic loads. Multiple NDE technologies were used to assess two concrete decks of a similar design, construction, age, and environment, but with different traffic conditions. The complementary use of multiple NDE technologies identified corrosion as the primary cause of damage in both decks. The severity of deterioration differed at the time of the survey, which caused the estimated remaining life of the two decks to differ by about 10 percent.

Aging and deterioration of bridges in the United States mandates strategies for bridge maintenance, rehabilitation, and repair. Bridge decks deteriorate faster than all other bridge components, because of the routine application of deicing salts, repeated freeze–thaw cycles, direct application of traffic loading, and other damaging effects. Concrete bridge deck performance was identified as one of the key bridge performance issues in the Federal Highway Administration's Long-Term Bridge Performance Program (*1*). To improve the understanding of the mechanisms and timing of bridge deck deterioration because of the effects of age, material types, traffic loading, and climatic conditions, high-quality performance data should be collected over an extended period of time, and condition assessment should be conducted periodically.

Given the large, diverse population of bridges throughout the United States, one of the most significant challenges for the Long-Term Bridge Performance Program was selecting representative bridges. The sampling challenge was mitigated by the selection of reference bridges and representative clusters of bridges in the same vicinity as the reference bridges that have similar characteristics (age, type, climate, and maintenance practices). This selection helped in the comparison of the performance of concrete bridge decks in similar geographical areas, but that, for instance, carry different traffic loads, to ascertain the influence of traffic load on deck performance.

The common practices of state transportation departments for condition assessment and monitoring concrete bridge decks have been visual inspection, sounding methods, and destructive methods. Although visual inspection and sounding methods have their merits, they are limited when used for the early detection and characterization of defects. Similarly, although destructive testing usually provides reliable assessment of the structure, the time and effort of such tests make this type of test impractical. As a result, the need emerged for nondestructive evaluation (NDE) technologies that can qualitatively and quantitatively assess the condition of concrete decks.

The qualitative nature of NDE data helps capture deterioration progression, and the quantitative nature of NDE assists in developing more reliable deterioration, predictive, and life cycle cost models. Since concrete decks are affected by various deterioration processes, multiple NDE technologies should be used for condition assessment. The NDE technologies that are commonly used to assess and monitor the condition of bridge decks include impact echo (IE), ground penetrating radar (GPR), half-cell potential, ultrasonic surface waves (USW), and electrical resistivity (ER). In addition to providing comprehensive information about the condition of the deck, combining the results of different NDE technologies increases the confidence level of detection.

This paper demonstrates the ability of the mentioned NDE technologies to monitor deck performance and capture the progression of deterioration over time, and compares the deck deterioration of two highly similar bridges in the same cluster.

DESCRIPTION OF BRIDGES

This study was performed on the twin bridges carrying northbound and southbound U.S. Route 15 over Interstate 66 (I-66) in Haymarket, Virginia. The southbound bridge (structure number 14178) and the

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northbound bridge (structure number 14180) are 276 ft (84.1 m) long and 42 ft (12.8 m) wide, and were built in 1979. Each bridge is a two-span, six-girder, steel built-up superstructure (Figure 1*a*) with a bare, cast-in-place 8 in. (200 mm) thick reinforced concrete deck constructed with removable forms. The southbound and northbound bridges carry two lanes of traffic. Traffic counts suggest a 38/62 directional split northbound/southbound, based on a 24 h turning movement count at the I-66 westbound off-ramp intersection. It stands to reason that traffic is heading southbound to eastbound in the mornings and westbound to northbound in the afternoons, and the afternoon traffic would not be traveling over the northbound bridge. In other words, a majority of the traffic comes from the north on U.S. Route 15, crosses the southbound bridge, and turns left onto eastbound I-66 in the morning. In the evening, that returning traffic would approach the interchange on westbound I-66, take the exit ramp, and turn right onto northbound U.S. Route 15 and never cross the northbound bridge.

The deck condition (including corrosion, deterioration, delamination, and concrete degradation condition maps) of the southbound bridge has been monitored four times since 2009, most recently in May 2015. The NDE results from the periodic surveys will be used to better understand deck performance and monitor the progression of deck deterioration over time. The deck of the northbound bridge was assessed for the first time in May 2015. To demonstrate the effect of traffic load on the performance and deterioration of concrete decks, the current conditions of the northbound and southbound bridges was compared through multiple NDE condition maps. All the NDE measurements were made on a 2 by 2 ft (0.6 by 0.6 m) grid, except for the GPR surveys, which were conducted in the longitudinal direction of the bridge with survey lines 2 ft (0.6 m) apart. It took two 5 h (total 10 h) lane closures to survey the bridges. In other words, considering that the surveyed deck area of each bridge was about 11,000 ft^2 (1,020 m^2), the surveys were conducted at production rates of about 1,100 ft^2 (102 m^2) per hour. A section of the deck surface of the southbound bridge with clearly visible patches and spalling is shown in Figure 1*b*.

(a)

(b)

FIGURE 1 Study bridges on U.S. Route 15 in Haymarket, Virginia: (*a*) side view of the northbound bridge and (*b*) deck surface of the southbound bridge.

NDE TECHNOLOGY DESCRIPTIONS AND RESULTS

Corrosion Assessment by Electrical Resistivity

Rebar corrosion leads to concrete deterioration, delamination, contamination, and loss of rebar section. If the damage is not repaired in a timely manner, it will cause large cracks and areas of delamination, ultimately leading to spalling of concrete. Chloride ions typically penetrate from the surface into a bridge deck, resulting in a higher chloride concentration and creating a more corrosive environment. A corrosive environment and its correlated corrosion rate can be evaluated by the ER method. The ER of concrete decreases as the moisture and chloride concentration increases (*2*). It has been observed that a resistivity of less than 5 kOhm-cm supports very rapid rebar corrosion (*3*). A four-point Wenner probe was used for resistivity measurements (Figure 2).

Assessment of the progression of corrosion is illustrated in Figure 3, *a* and *b,* with condition maps obtained from the ER surveys of the southbound deck, which was surveyed in 2009 and 2015. The ER maps in Figure 3 describe concrete resistivity in kOhm-cm. The threshold for a corrosive environment was identified to be 30 kOhm-cm based on correlations with other NDE methods. It can

FIGURE 2 Electrical resistivity survey.

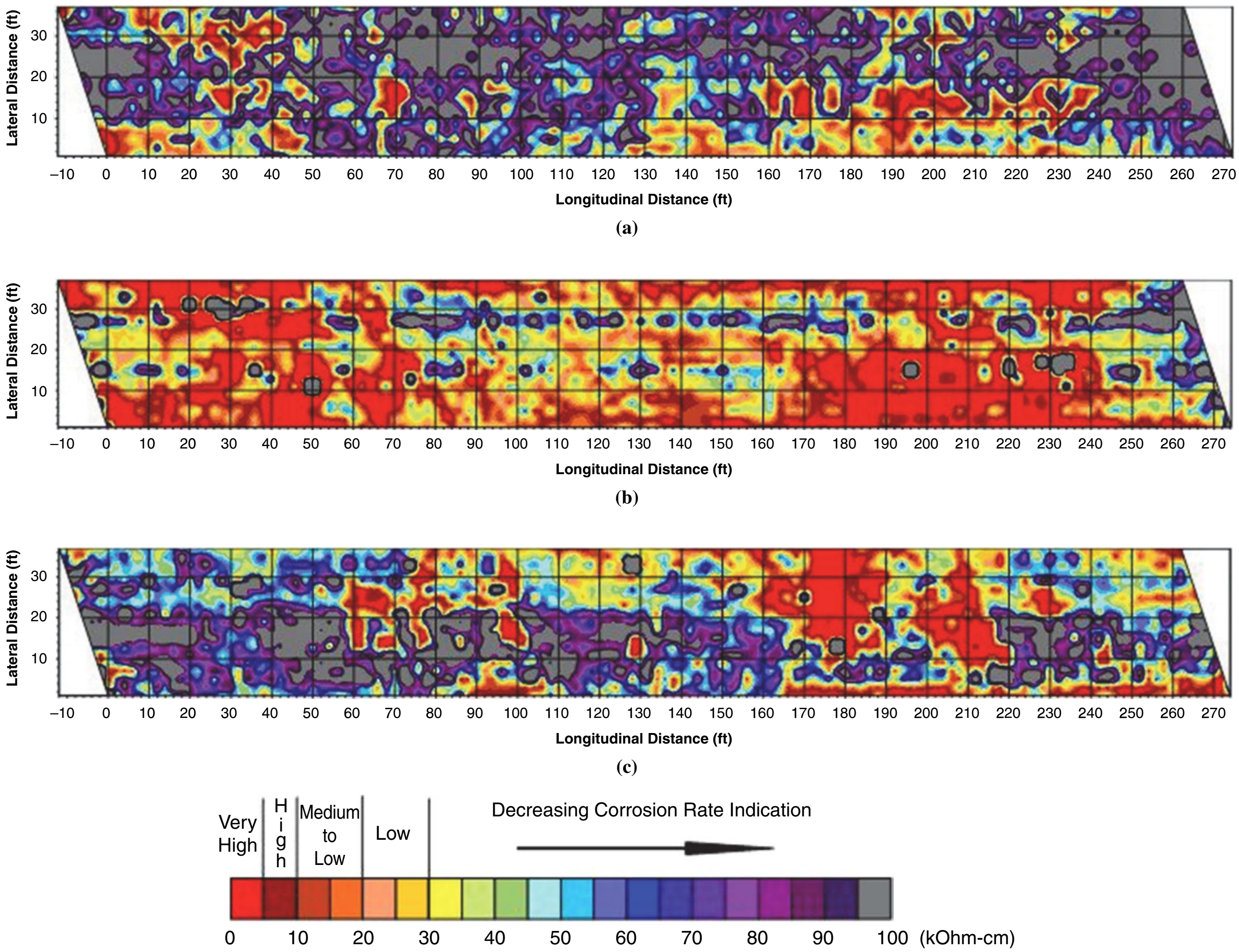

FIGURE 3 Corrosion assessment maps from ER surveys conducted on (*a*) the southbound bridge deck in 2009, (*b*) the southbound bridge deck in 2015, and (*c*) the northbound bridge deck in 2015.

be clearly observed qualitatively from Figure 3, *a* and *b*, that ER captured corrosion progression during the 6-year period. Expansion of the areas affected by corrosion and increase in the severity of the corrosive environment in 2015 occurred in the same areas that were identified as corrosive in 2009. A qualitative comparison of the current corrosion condition of the southbound and northbound decks (Figure 3, *b* and *c*) indicated that the southbound deck had larger areas with a highly corrosive environment and that the severity of corrosion processes was higher.

Since the data obtained from NDE technologies are quantitative, they can be used to assess the condition of decks quantitatively and compute a condition assessment number. The condition assessment number combines the effect of the extent and severity of deterioration obtained from the NDE surveys. The NDE measurements and the calculated condition assessment numbers, which vary from 100 for the best condition to 0 for the worst, could be entered in bridge management systems to assist bridge owners in data-driven decision making for maintenance, rehabilitation, or replacement of the deck. For example, most transportation agencies already have criteria for various levels of intervention based on the assessment of deck area affected by delamination or corrosion, where corrosion assessment is obtained through chloride concentration or half-cell potential measurements. The condition assessment number for each type of defect is calculated as a weighted average of the percentages of the deck area, with different severity levels of that specific defect. The area described as sound is assigned a weight factor of 100. The area with a fair to poor grade is assigned a factor of 50, and the area in the state of severe condition is assigned a factor of 0.

The ER-based corrosion condition assessment numbers along with the percentages of the deck areas with various levels of anticipated corrosion rates are compared in Table 1 for the three ER surveys. The four corrosion states are defined by four ER ranges: less than 10 kOhm-cm as high, 10 to 20 kOhm-cm as moderate, 20 to 30 kOhm-cm as low, and above 30 kOhm-cm as very low. The corrosion condition assessment number for the southbound deck dropped from 86 to 41 in 6 years. The overall decrease in condition assessment numbers is reflected in the increase in deck area at different severity levels of corrosion. The majority of the southbound deck area had very low corrosion rates in 2009, and high to moderate corrosion rates in 2015. The corrosion condition assessment number for

TABLE 1 Corrosion Assessment from ER: Condition Assessment Number and Percentages of Deck Area

Bridge (Year)	Condition Assessment Number	Distribution (%) by Corrosion State			
		Very Low	Low	Moderate	High
Southbound (2009)	86.3	72	15	10	3
Southbound (2015)	40.9	22	17	17	44
Northbound (2015)	72.1	61	12	8	20

[a]Corrosion states as defined by range of electrical resistivity.

the northbound deck (mostly with very low corrosion rates) was 72 in the 2015 survey, which was higher than the corrosion condition assessment number for the southbound deck surveyed in the same year, but lower than for the northbound deck in 2009.

Ground Penetrating Radar

A GPR survey can be used for a qualitative assessment of the deck condition by measuring the attenuation of electromagnetic waves on the top rebar level (*4*). The amplitude of the reflection will be highest when the deck is in a good condition. The presence of moisture, chloride ions, iron oxide, cracks, and air-filled delaminations alters the dielectric properties and increases the attenuation of the electromagnetic waves. Thus, zones of highly-attenuated signal in GPR attenuation maps indicate locations of likely concrete deterioration, delamination, or corrosive environment. A GPR survey that was conducted with a 1.5 GHz ground coupled antenna is shown in Figure 4.

GPR condition maps obtained from GPR surveys of the southbound deck in 2009 and 2015 are shown and compared qualitatively in Figure 5, *a* and *b*. The GPR threshold levels of deterioration are specific to the bridge conditions and equipment used, and were obtained from correlations with other NDE technologies. The correlations between the attenuation levels and condition grades are indicated in the figure. A serious condition is described for both bridges with attenuation level of below –20 dB. Similar to ER, GPR qualitatively captured deterioration progression in the southbound deck during the 6-year period. The progression and level of deterioration correlate well with the corrosion progression captured by the ER surveys. The 2015 GPR deterioration condition maps of the southbound and northbound decks are qualitatively similar to their corresponding ER corrosion condition maps. The similarity can be attributed to the fact that both measurements are primarily affected by the same elements affecting the electrical conductivity and dielectric value of concrete: moisture, chlorides, salts, etc. Similar to the corrosion condition of the decks indicated by ER testing, the GPR condition maps in Figure 5, *b* and *c*, indicate that the southbound deck is more deteriorated compared with the northbound deck.

To quantify the progression of deterioration, the condition assessment numbers along with the percentages of the deck areas at various severity levels of deterioration are compared in Table 2 for the three GPR surveys. The GPR condition assessment number for the southbound deck dropped from 48 in 2009 to 22 in 2015. A large percentage of the southbound deck area was in a poor condition in 2009, while most of the southbound deck area is currently in a serious condition. The current GPR condition assessment number for the northbound

FIGURE 4 GPR survey using a 1.5 GHz ground coupled antenna.

deck is 38. Most of the southbound deck area is in serious condition, while the northbound deck, which was surveyed at the same time, is mostly in poor condition.

Impact Echo

Concrete delamination is most often a result of rebar corrosion, although other types of concrete deterioration or repeated overloading, or a combination of those, can also lead to delamination. IE has been successfully implemented in detecting and characterizing delamination in bridge decks (*5*). IE measurements can be made with a single IE probe, consisting of an impactor and a nearby receiver (Figure 6*a*) or with multiple IE probes (Figure 6*b*), each consisting of an impactor and a sensor.

The primary objective of IE testing is to locate reflectors (at the bottom of the deck or a delamination) in the deck. The extent and position of reflectors can be estimated by analyzing the frequency response of the waves reflected from the reflector. The results from IE surveys on the northbound and southbound bridges are shown in Figure 7. The delamination grades from IE surveys are defined based on the measured dominant response frequencies. The condition is described as good or sound when the depth of the reflector based on the measured response frequency matches the thickness of

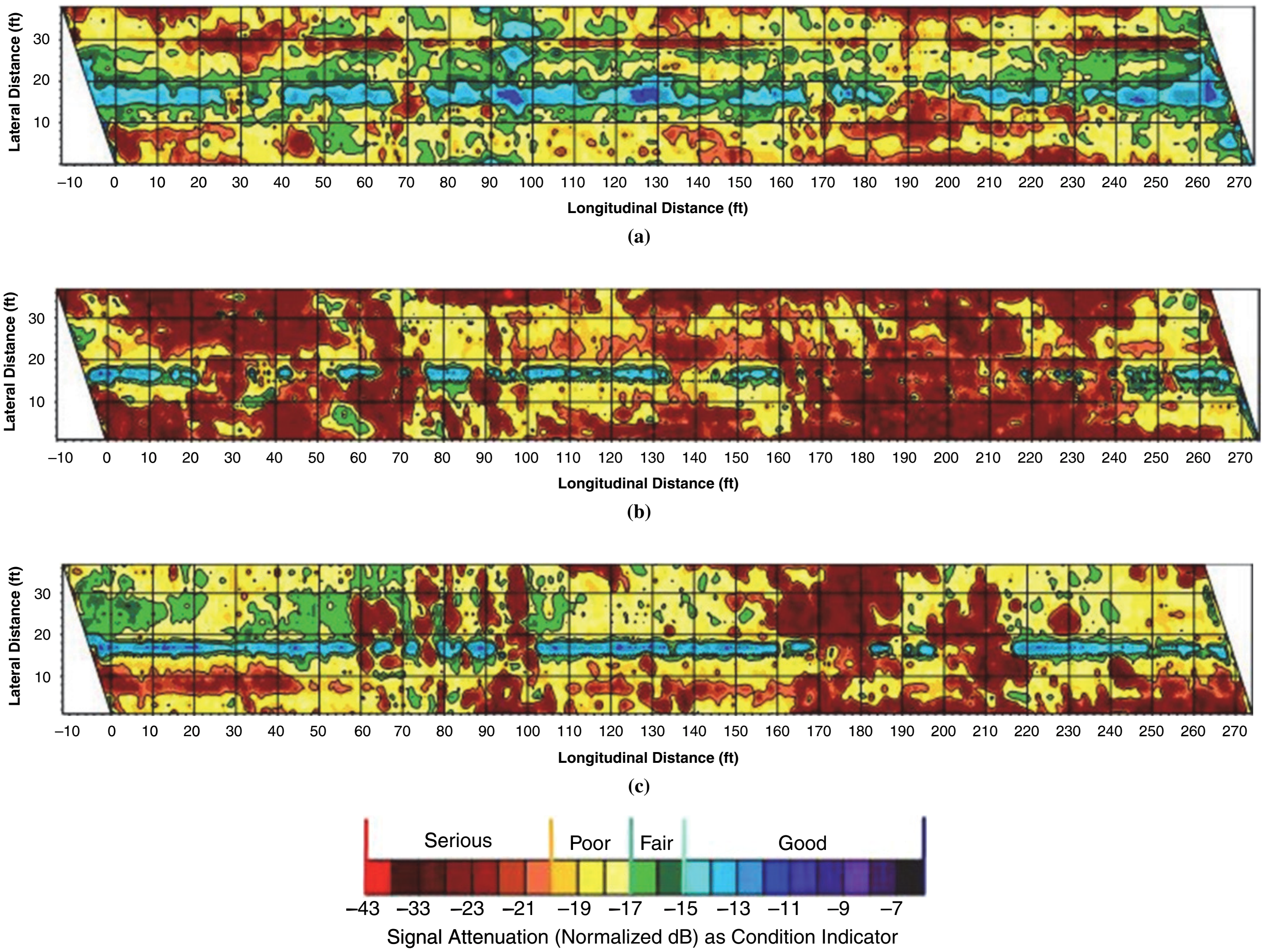

FIGURE 5 Deterioration condition maps from GPR survey on (*a*) the southbound bridge deck in 2009, (*b*) the southbound bridge deck in 2015, and (*c*) the northbound bridge deck in 2015.

the deck. In the case of a delaminated deck, reflections of the compression wave occur at shallower depths, causing a shift in the response spectrum toward higher frequencies. Depending on the extent and continuity of the delamination, the partitioning of energy of waves being reflected from the bottom of the deck and delamination may vary. Initial delamination (fair condition) is described as occasional separations between the two deck zones. Thus, it will have two distinct peaks corresponding to reflections from the bottom of the deck and the delamination. Progressed delamination (poor condition) is characterized by a single peak at a frequency corresponding to the depth of the delamination. Finally, in cases of wide or shallow delaminations, the dominant response of the deck to an impact is characterized by a low-frequency response of flexural mode oscillations of the upper delaminated portion of the deck. This condition is graded as a serious condition and is always in the audible frequency range.

TABLE 2 GPR Assessment: Condition Assessment Number and Percentages of Deck Area

Bridge (Year)	Condition Assessment Number	Distribution (%) by Level of Deterioration			
		Good	Fair	Poor	Serious
Southbound (2009)	48.1	14	24	41	21
Southbound (2015)	22.4	5	5	35	55
Northbound (2015)	38.2	9	14	48	29

Figure 7, *a* and *b*, depicts the condition of the southbound deck obtained from the IE surveys conducted in 2009 and 2015. The maps illustrate the progression of delamination during the 6-year period. The delamination condition map of the northbound deck surveyed in 2015 is shown in Figure 7*c*. The overall delamination condition of the northbound deck is sound to fair, while the majority of the southbound deck is in poor to serious condition.

Similar to the ER and GPR results, the condition assessment numbers from the three IE surveys, along with the percentages of the deck areas at various severity levels of delamination, are compared quantitatively in Table 3. The delamination condition assessment number for the southbound deck dropped from 69 in 2009 to 40 in 2015. Although a large percentage of the southbound deck area was sound in 2009, the majority of the southbound deck was extensively

(a) (b)

FIGURE 6 Two types of IE testing systems: (*a*) an IE cane and (*b*) a stepper.

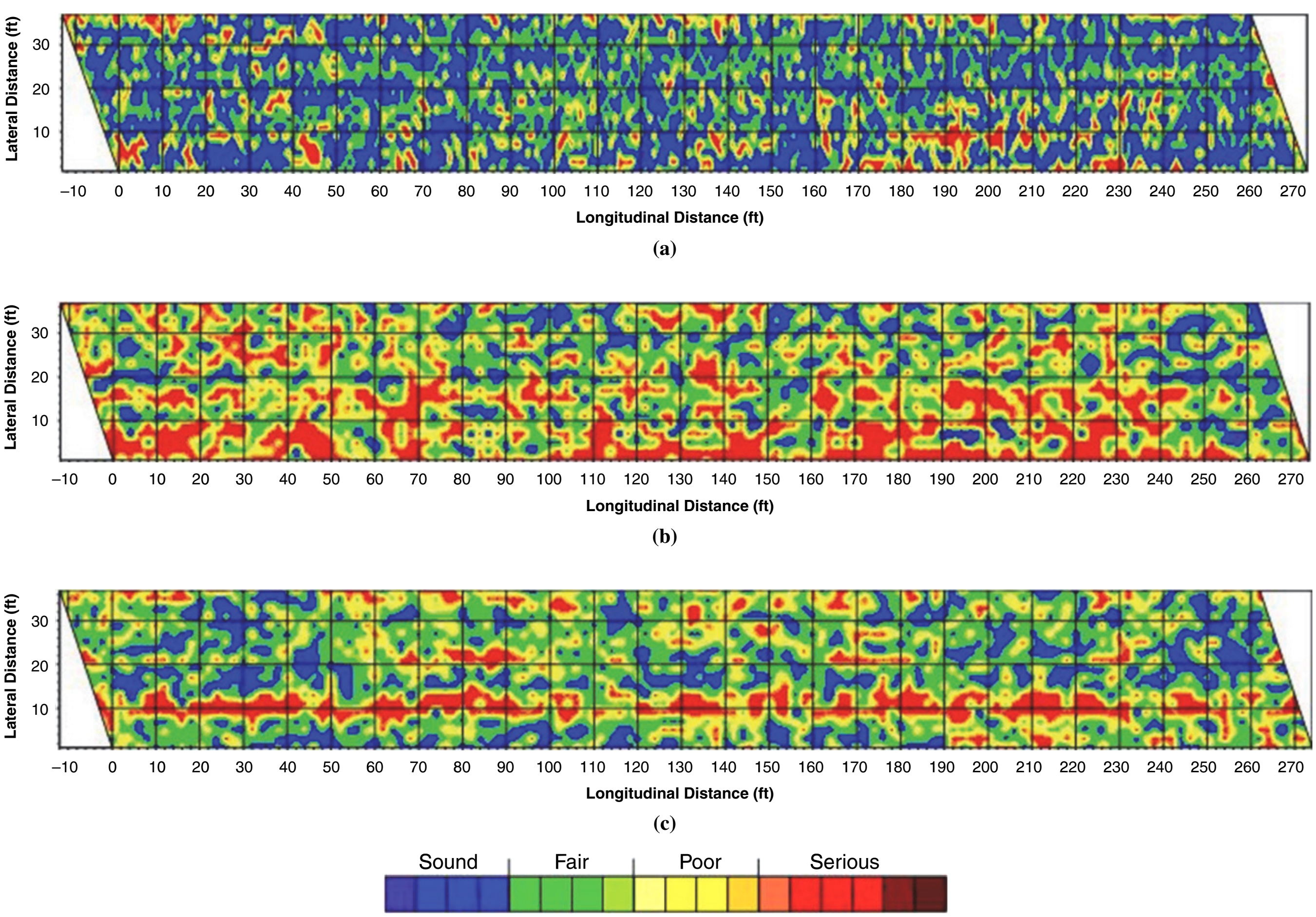

FIGURE 7 Delamination maps from IE surveys conducted on (*a*) the southbound bridge deck in 2009, (*b*) the southbound bridge deck in 2015, and (*c*) the northbound bridge deck in 2015.

TABLE 3 Delamination Assessment from IE: Condition Assessment Number and Percentages of Deck Area

Bridge (Year)	Condition Assessment Number	Distribution (%) by Level of Delamination			
		Sound	Fair	Poor	Serious
Southbound (2009)	69.5	54	26	4	15
Southbound (2015)	39.9	21	31	7	41
Northbound (2015)	52.1	28	34	14	24

delaminated in 2015. The delamination condition assessment number for the northbound deck in 2015 was 52. This value is consistent with the larger distribution of extensive delamination in the southbound deck compared with the northbound deck in the same year.

Ultrasonic Surface Waves

In addition to corrosion, several other deterioration processes occur in bridge decks as a result of repeated freeze and thaw, alkali-silica reaction, mechanical stressing, and overloading. These factors may lead to expansive stresses (cracks) in the concrete and either reduced mechanical properties or altered dielectric properties. The USW method is effective for assessing concrete degradation and detecting and measuring changes in mechanical properties. Surface waves are stress waves traveling along the surface of the deck, with their body extending to the depth of approximately one wavelength (*6*). Therefore, as long as the USW testing is limited to the wavelengths comparable to the deck thickness, the surface wave velocity will be controlled by concrete properties (elastic modulus). Devices like the portable seismic property analyzer, shown in Figure 8, can be used in the evaluation of concrete modulus by the USW method. A variation in the concrete modulus in the deck does not necessarily mean deterioration. Such variations can often be introduced at the time of construction because of material variation and placement procedures. Therefore, only a periodic measurement of changes in the concrete modulus would lead to the identification of deterioration processes.

Concrete quality maps of the southbound deck are shown in Figure 9, *a* and *b*, for the USW surveys conducted in 2009 and 2015, respectively. Areas of very low concrete modulus obtained from the USW testing are, in general, at locations of delamination. Similar to the IE results, the concrete quality of the southbound deck, in concrete modulus, decreased in 2015, compared with the quality from the USW survey conducted in 2009. Figure 9, *b* and *c*, indicates that the current concrete quality of the northbound deck is greater than that of the southbound deck.

The results from the three USW surveys are presented quantitatively in Table 4 in percentages of the deck areas with various concrete elastic moduli. The quality of concrete in the southbound deck did not change much from 2011 to 2015. A large percentage of the southbound deck area had a modulus of less than 3,500 kips per square inch (ksi) (24 GPa). A comparison of the distribution of the various levels of modulus in the northbound and southbound decks indicates that the concrete quality of the northbound deck is greater than that of the southbound deck.

Comparison of the 2015 quantitative results for the northbound and southbound bridges shows greater deterioration of the deck of the southbound bridge. Considering that the two bridges are of the same age, design, and construction practices, and are exposed to equal environmental conditions but different traffic loads, the first cause of the better condition of the northbound deck seems to be traffic counts. The other potential cause of the better condition of the northbound bridge deck might be better initial concrete quality of the northbound deck at the time of construction. Figure 10 presents the conditions of the two bridge decks over time. The deterioration curves for corrosion, delamination, and GPR-based condition assessment are plotted for the southbound bridge based on the results of

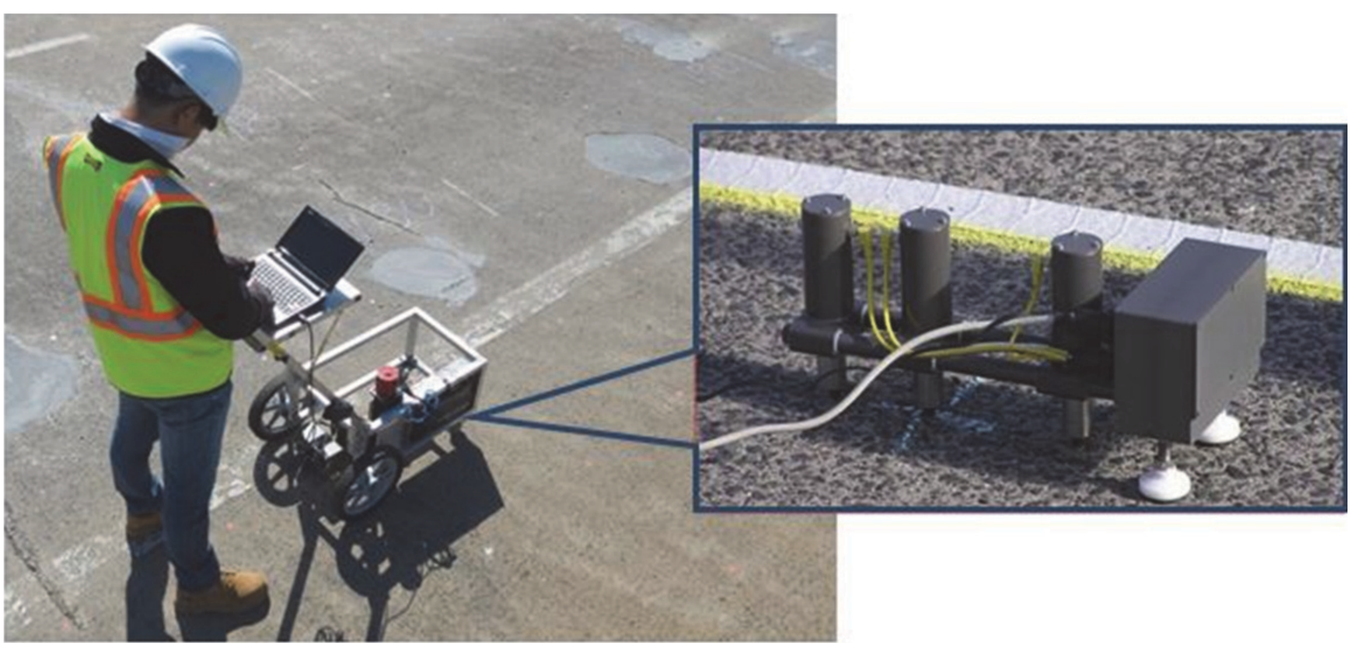

FIGURE 8 Surface wave testing using a portable seismic property analyzer.

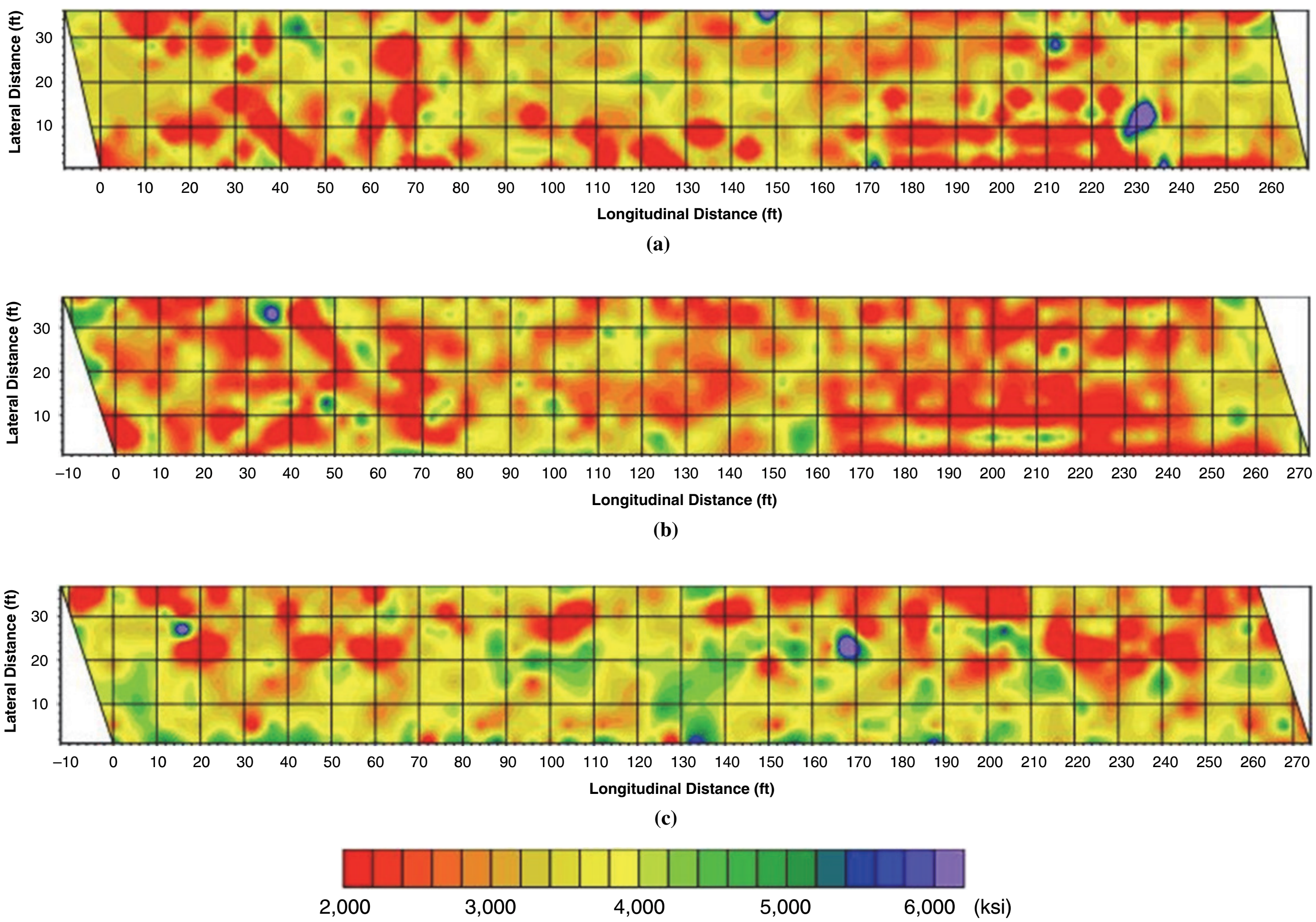

FIGURE 9 Concrete modulus maps from USW surveys conducted on (*a*) the southbound bridge deck in 2009, (*b*) the southbound bridge deck in 2015, and (*c*) the northbound bridge deck in 2015.

surveys in 2009, 2011, and 2015. The same three condition assessment numbers for the northbound bridge for 2015 are marked by circles. As marked in the figure, the deterioration condition assessment numbers for the northbound bridge are only 3 to 4 years distant from the comparable condition assessment numbers for the southbound bridge. This finding can be interpreted as indicating that, assuming similar deterioration patterns for the two bridges, the remaining life of the northbound bridge is expected to be 3 to 4 years longer than that of the southbound bridge. The finding also means that the life spans of the two decks differ by approximately 10%.

TABLE 4 Concrete Quality Assessment from USW: Average Modulus and Standard Deviation

	Distribution (%) by Modulus				
Bridge (Year)	<3,500 ksi	3,500–4,500 ksi	>4,500 ksi	Mean *E* (ksi)	SD (ksi)
Southbound (2011)	66	29	5	3,286	705
Southbound (2015)	68	27	5	3,008	988
Northbound (2015)	48	41	11	3,514	1,582

NOTE: 1 ksi = 6.89 MPa.

CONCLUSIONS

The condition of the deck of the southbound U.S. Route 15 bridge in Haymarket, was monitored over a period of 6 years to improve knowledge about bridge deck performance and to understand the rates of progression of different deterioration and defect types over an extended period of time. The current conditions of the northbound and southbound decks were compared to improve understanding the correlation of deterioration of bridge decks with similar design, construction, age, and environment, but with different traffic loads.

The results of the surveys over a 6-year period show that NDE technologies have the ability to monitor the progression of deterioration over time, whether qualitatively through increase of deteriorated areas or quantitatively through changes in condition assessment numbers. Expanding deterioration and increasing severity of deterioration in 2015 occurred in the same areas that were identified as deteriorated in 2009 in all the NDE condition maps. The condition assessment numbers facilitate the development of more objective and realistic deterioration and prediction models for the northbound and southbound bridge decks.

The complementary use of multiple NDE technologies identifies corrosion as the primary cause of damage in the northbound and southbound decks. Qualitative and quantitative comparisons

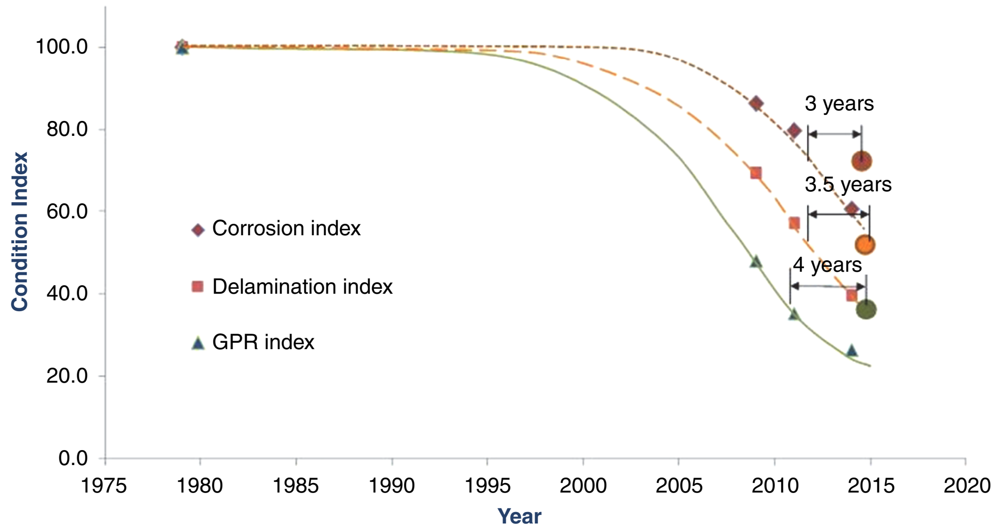

FIGURE 10 Deterioration curves for the southbound deck and condition assessment number for the northbound deck.

of the NDE results for both decks demonstrate that the southbound deck is more damaged and deteriorated. The difference between the two bridges is attributed to differences in traffic counts and possibly to the initial concrete quality of the two decks. The evaluated differences in condition assessment numbers are estimated to reflect a difference of 10% in the life span, or remaining life, of the two bridge decks.

The NDE results provide strong correlation between the ER and GPR condition maps, which is explained by the similar electrical properties affecting the two. Additional correlations were established for delamination detection between GPR and IE, and USW and IE, and concrete degradation between USW and GPR. These correlations also point to corrosion as the primary cause of deterioration for these decks.

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