RESILIENT INFRASTRUCTURE
June 1–4, 2016

EVALUATION OF NDT TECHNIQUES FOR CONCRETE BRIDGE DECKS USING FUZZY ANALYTICAL HIERARCHY PROCESS

Tarek Omar
PhD Candidate, Western University, Canada

Moncef Nehdi
Professor, Western University, Canada

ABSTRACT

Considering the colossal backlog of deteriorating bridges, transportation agencies need to systematically evaluate bridge deck conditions in order to optimize the timing, scope, and approach of preventive maintenance, repair, and replacement. Over the last few years, there have been growing interest among bridge infrastructure stakeholders in using non-destructive methodologies for bridge inspection, evaluation, and maintenance. Nondestructive testing (NDT) techniques can provide needed information about the “under-the-surface” deteriorated condition of bridge decks. This paper examines the most common NDT technologies for assessing bridge decks. Each technology was rated based on five performance measures: capability to detect subsurface defects, speed of data collection, simplicity of analysis and interpretation, accuracy of results, and cost of measurement. The study has particular emphasis on reinforcement corrosion, delamination, and internal cracking. The information sought to identify the significance of the factors affecting the analysis process was collected through a survey questionnaire. In order to incorporate the imprecise information and vagueness of human judgment in the decision-making, the fuzzy analytical hierarchy process (FAHP) is employed, as per the fuzzy preference programming method. Results demonstrate the capabilities of each technology and its ability to address bridge challenges. In order to assist bridge engineers and decision makers, recommendations were made with respect to the selection of the most appropriate technologies to identify specific deterioration mechanisms.

Keywords: Concrete deterioration, bridge deck, condition assessment, NDT technologies, fuzzy, analytical.

1. INTRODUCTION

Concrete bridges experience loss of integrity and changes in resistance that are time variant, due to environmental exposure, various deterioration mechanisms, and excessive mechanical loading. Deterioration processes in concrete bridges are caused by chemical (e.g. alkali-silica reaction, carbonation, corrosion, crystallization, leaching, sulfate and acid attack), physical (e.g. freezing-thawing cycles, creep, fatigue, shrinkage, abrasion, erosion), mechanical (e.g. static and/or dynamic loads, construction faults such as those from premature loading during construction), and biological mechanisms (e.g. accumulation of organic matter, living organisms, fungi, and moss) (Penttala, 2009). Some mechanisms primarily affect the reinforcement and some others affect the concrete itself. Such degradation mechanisms can compromise the serviceability and structural integrity. Different deterioration processes lead to different types of structural defects (e.g. delamination, spalling, cracking, rebar size reduction) or material alterations (e.g. reduced modulus, changed electrical and chemical properties). However, deterioration is commonly initiated by rebar corrosion, followed by cracking, delamination and spalling of concrete (Gucunski and Nazarian, 2010). It can lead to structural and functional failures, which are catastrophic, both in terms of human life and economic loss.

Most bridges in Canada and the United States are 40–60 years old. Thus, the need to rehabilitate bridges will increase dramatically over next 20 years. According to the Canadian infrastructure report card (2016), 26% of bridges are in fair, poor or very poor condition. The United States’ 2013 infrastructure report card indicates that an annual investment of $20.5 billion would be needed to eliminate the backlog of deficient bridges in the USA by year

2028. A significant part of the cost accounts for the repair and replacement of concrete decks. Regular inspection and routine maintenance, rehabilitation and replacement (MR&R) are needed to keep the bridges in good condition. Performing effective bridge condition assessment is vital to predict the progress of deterioration, to provide required inputs for optimizing bridge MR&R needs, and to ensure sustainability of the bridge infrastructure. Subjective or inaccurate condition assessment is the most critical technical barrier to effective management of highway bridges since visual inspection is the default bridge inspection methodology, whereas its results heavily depend on the expertise and judgment of bridge inspectors.

The evaluation of concrete bridges is complex due to the composite material nature of concrete. The application of nondestructive testing (NDT) technologies is one of the effective ways to monitor and predict concrete bridge deterioration. NDT approaches enable the detection of deterioration processes at its early stages and can be incorporated into the inspection process to evaluate hidden defects such as reinforcing steel corrosion or crack propagation. The use of simple nondestructive methods such as chain drag and hammer sounding are inexpensive methods, typically yielding primarily qualitative and subjective decisions. Advanced NDT of concrete bridges has its origins in geophysics. A number of techniques introduced exploit various physical phenomena (acoustic, seismic, electric, electromagnetic, and thermal, etc.) to detect and characterize specific deterioration processes or defects. In general, all the techniques utilize an approach where the objective is to learn about the characteristics of the medium from its response to the applied excitation (Gucunski et al., 2013). The most commonly used NDT methods in onsite assessment and evaluation of reinforced concrete bridge decks are evaluated and ranked in this study based on a set of flexible multi-attributed criteria and sub-criteria, developed to form a hierarchical decision.

2. RESEARCH OBJECTIVES AND METHODOLOGY

The aim of this study is to conduct a comparative analysis of the NDT methods for detection of subsurface defects in concrete bridge decks. To achieve this goal, the following objectives are pursued: (1) study the commonly used NDT technologies in assessing concrete bridge decks; (2) develop a fuzzy hierarchical decision model to evaluate the different methods; and (3) recommend the most appropriate technologies to identify specific deterioration mechanisms to assist bridge engineers and decision makers. The methodology adopted for achieving of these objectives consists of: (1) conduct literature survey on bridge condition assessment using NDT technologies; (2) identify a set of flexible multi-attributed evaluation criteria and sub-criteria; (3) collect information from participants representing different bridge community organizations; (4) apply fuzzy set theory to the analysis and calculate the relative weights for the different elements in the hierarchy; (5) rank the NDT methods based on their scores; and (6) guideline the bridge community for the selection of appropriate technologies.

3. MODEL DEVELOPMENT

The Analytic Hierarchy Process (AHP) is a decision support and analysis tool that has found extensive applications in multi-attribute decision making problems and is widely applied in bridge management. The AHP, developed by Saaty (1980), is based on modeling decision problems into multiple layers of criteria and sub-criteria to form a decision hierarchy. This is followed by a series of pairwise comparisons among elements in the same layer to decide on their relative importance/influence.

3.1 Selection of Deterioration Types, Performance Measures and NDT Alternatives

The study has particular emphasis on the most serious types of subsurface defects present in concrete bridge decks. Hence, the evaluation of NDT technologies was carried out for three deterioration types: delamination; reinforcement corrosion, and cracking. The rationale behind limiting the deterioration types into only three categories is: although there are different causes for deterioration, in most cases the causes cannot be determined by NDT technologies; only their consequences can be determined. For example, corrosion and shrinkage induced cracking will result in material degradation, which can be detected through reduced velocity, modulus, and so forth. In addition, from the list of all possible deterioration types and mechanisms, the three deterioration categories are believed to be of the highest concern to transportation agencies. The selected five performance measures for categorizing and ranking the technologies are: capability to detect subsurface defects, speed of data collection and analysis, simplicity of data collection and interpretation, accuracy of results, and cost of data collection and analysis. The rationale used for considering only five performance measures is: although the description of a particular performance provides a more detailed description of that performance in terms of a large number of measures, for most technologies there is either no information regarding a specific performance measure or the measure is not applicable to that particular technology. No other measures are believed to affect the evaluation outcomes. In addition, analyses in terms of a smaller number of performance measures are supposed to be of higher interest and practical value to transportation agencies and industry. The research then identified and selected a number of sub-criteria to proceed with the comparative analysis in an accurate, repeatable, and practical manner as follows: (1): capability where the selected NDT methods were evaluated against their capabilities for detection the three sub-surface deterioration types; (2) speed where the selected NDT methods were evaluated against the speed of data collection, speed of data analysis, and the importance of having an automation process; (3) simplicity where the selected NDT methods were evaluated against the importance of having an experienced operator and analyzer as well as the effects of the environment and traffic on data collection; (4) accuracy where the selected NDT methods were evaluated against their accuracy in detecting the defect's location, depth and severity; and (5) cost where the selected NDT methods were evaluated against their associated equipment, data collection, and data analysis cost.

A number of NDT technologies are currently used in bridge deck evaluation. A survey of literature suggests that the most commonly used NDT methods in onsite assessment and evaluation of reinforced concrete bridge decks are impact echo (IE), seismic or ultrasonic pulse velocity (PV), ground penetrating radar (GPR), infrared thermography (IRT), half-cell potential (HCP) and electrical resistivity (ER). The five selected NDT technologies have the following roles with respect to the three deterioration types. With respect to corrosion, HCP detects active corrosion, while ER and GPR evaluate conditions for a corrosive environment. With respect to internal cracking, PV provides information about the degradation of the concrete's elastic modulus. With respect to delamination, IE and IRT detect delamination (Yehia et al., 2007). Figure 1 illustrates the developed hierarchy structure of the performance parameters and the sub-criteria along with the evaluated NDT alternatives.

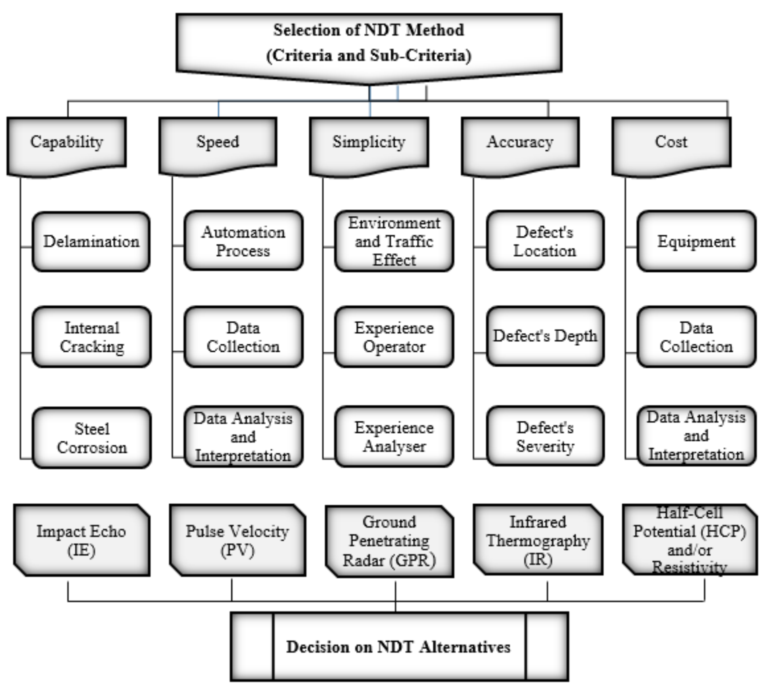

Figure 1: Hierarchy framework for selection of NDT technique.

4. SURVEY QUESTIONNAIRE

The different hierarchal elements in the model require relative importance weights. Therefore, pairwise comparisons were assigned to elements of the assessment hierarchy using the scale developed by Saaty. The pairwise comparisons data was gathered through a constructed questionnaire survey. The survey collects opinions from bridge and NDE experts for identifying the significance of the factors affecting the selection of NDT methods for detecting subsurface defects in concrete bridge decks. Experts representing different bridge community organizations (Canadian ministries and US departments of transportation, NDT contractors and consultants, and researchers) participated in the survey. A total of 35 experts accepted to participate in the questionnaire. Of the 35 experts, a total of 27 responses were received, a 77% response rate. The relatively high response rate is a good indicator of adequate survey design. Figure 2 illustrates a summary of information based on the respondents' organizations and their experience. The questionnaire was created using an online survey website service for ease of distribution and to minimize the time required to take the survey.

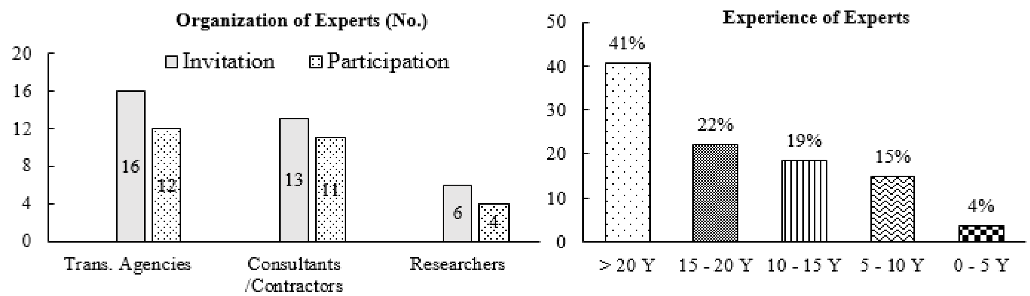

Figure 2: Organization and experience of participants in the survey questionnaire.

The questionnaire consisted of four sections: the first section aimed to obtain general information of the participants' contact information, organization and experience in the bridge and NDT community; the second section aimed to identify the frequency and type of NDT method(s) being used in their bridge schemes; the third section was divided into two parts: part (i) aimed to seek the degree of importance between the five main performance parameters with respect to the selection of the NDT method, while part (ii) sensed the degree of importance between the sub-criteria with respect to the related main performance parameter; and the fourth section aimed to seek the degree of importance of employing the selected NDT alternatives with respect to each of the fifteen sub-criteria. For example, the experts were asked to provide the degree of importance of utilizing IE if compared with utilizing each of the other methods with respect to their capabilities of detecting delamination as illustrated in Figure 3.

Example: in the table below, consider comparing the "Impact Echo method" (Criterion Y) with the "Infrared Thermography method" (Criterion X) with respect to "the capability of detecting subsurface delamination".

Criterion	←				**Degree of Importance**				→	**Criterion**
(X)	**(9)** Absolute	**(7)** Very Strong	**(5)** Strong	**(3)** Moderate	**(1)** Equal	**(3)** Moderate	**(5)** Strong	**(7)** Very Strong	**(9)** Absolute	**(Y)**
					Detection of Subsurface Delamination					
Pulse Velocity										Impact Echo
Ground Penetrating Radar										
Infrared Thermography			✓		✓				✓	
Half-Cell Potential										

If you consider that the Infrared Thermography method is more important than the Impact Echo method in detecting the subsurface delamination, and the degree of importance is "Strong".

If you consider that both Impact Echo and Infrared Thermography methods have "Equal" importance in detecting the subsurface delamination.

If you consider that the Impact Echo method is more important than the Infrared Thermography method in detecting the subsurface delamination, and the degree of importance is "Absolute".

Figure 3: Example of a question in the survey questionnaire.

5. MODEL IMPLEMENTATION

The pairwise comparisons in the AHP analysis process are performed using a 9-point fundamental scale of absolute values that represent the strength of judgements where 1 being the least favorable and 9 being the most favorable. The AHP uses an eigenvalue method to determine the normalized weights of all criteria and sub-criteria in the hierarchy where the intensities of the judgements are assembled in reciprocal matrices. Although, the AHP process has the advantage of allowing the decision maker to perform consistency checks for the provided judgement regarding the relative importance among the decision-making elements, the rankings produced by AHP are arbitrary because they result from a subjective response. The use of the discrete scale of 1 to 9 does not account for the uncertainty and imprecision associated with judgment during the pairwise comparison process. The fuzzy set theory (FST), first introduced by Zadeh (1965), is a natural way to capture the 'fuzziness' or the vagueness and uncertainty in the evaluation of alternatives. The vague data are represented using fuzzy numbers, which can be further subjected to mathematical operations in a fuzzy domain. Fuzzy numbers can be represented by its membership function ranging between 0 and 1. When comparing two elements, the uncertain numerical ratio is expressed in a fuzzy manner. The membership function of fuzzy numbers can take various shapes. Linear approximations such as triangular and trapezoidal fuzzy numbers are frequently used in construction applications. The Fuzzy AHP (FAHP) has been utilized in various decision making processes by several researchers (e.g. Huang et al., 2008; Bhattacharyya et al., 2011; Chang and Lee, 2012). Dealing with the fuzzy comparison matrices that result from the application of the "fuzzification" scale has also been the point of interest for many researchers (Mikhailov, 2004; Sasmal and Ramanjaneyulu, 2008; Huo et al., 2011). In order to make the evaluation analysis more precise, FAHP was utilized in the present study as an effective method to deal with the inherent fuzziness and uncertainty in judgment during the pairwise comparison process. The degree of relative importance from the received responses was utilized to construct the pairwise comparison matrices. Saaty's linguistic scale for importance was adopted and presented in Table 1, where the difference between most probable (actual response gathered) with the upper and lower values is equal to one. This fuzzification scale was applied to all the pairwise comparisons gathered from the questionnaire responses and all fuzzy evaluation matrices were developed using an Excel worksheet and used as input data for the FAHP analysis.

Table 1: Linguistic scales for importance

Linguistic scale for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Equally Important	(1,1,1)	(1,1,1)
Intermediate Level	(1,2,3)	(1/3,1/2,1)
Moderately Important	(2,3,4)	(1/4,1/3,1/2)
Intermediate Level	(3,4,5)	(1/5,1/4,1/3)
Important	(4,5,6)	(1/6,1/5,1/4)
Intermediate Level	(5,6,7)	(1/7,1/6,1/5)
Very Important	(6,7,8)	(1/8,1/7,1/6)
Intermediate Level	(7,8,9)	(1/9,1/8,1/7)
Extremely Important	(8,9,9)	(1/9,1/9,1/8)

The Fuzzy Preference Programing (FPP), introduced by Mikhailov (2004), can acquire the consistency ratios of fuzzy pairwise comparison matrices and the local weights can be solved by the Matlab software using a prioritization approach. The FPP method was utilized in this study to calculate the relative weights of the identified performance criteria and sub-criteria and also for the NDT alternatives with respect to each sub-criterion based on triangular fuzzy numbers. The solution to the prioritization problem in the FPP method is based on two main assumptions: the first assumption requires the existence of a non-empty fuzzy feasible area defined as the intersection of the membership functions and the simplex hyperplane; the second assumption specifies a selection rule, which determines a priority vector, having the maximum degree of membership in the the aggregated membership function. Considering the specific form of the membership functions, the maximum prioritization problem was first transformed into nonlinear programming formats based on their inequality constraints and then solved by an optimization function. For example, if the nonlinear equality constraint $x^2_1 + x_2 = 1$ and the nonlinear inequality constraint $x_1x_2 \geq -10$, it will be rewriten as $x^2_1 + x_2 - 1 = 0$; and $- x_1x_2 - 10 \leq 0$. Therefore, every triangular fuzzy number (lij, mij, uij), in all fuzzy evaluation matrices, was fist transformed as per Equations (1) and (2) below. It should be noted that as a triangular fuzzy comparison matrix is symmetric, therefore we only need to consider the constraints above the diagonal.

[1] $(mij - lij)*x(n + 1)*x(j) - x(i) + (lij)*x(j) \leq 0;$

[2] $(uij - mij)*x(n + 1)*x(j) + x(i) - (uij)*x(j) \leq 0.$

Matlab is a suitable tool for solving fuzzy decision-making problems where the local weights of fuzzy pairwise comparison matrices can be achieved using several optimization functions. The Matlab function "fmincon" attempts to find a constrained minimum of a scalar function of several variables starting at an initial estimate and is generally referred to as constrained nonlinear optimization or nonlinear programming. The full expression of the function and how it works can be found in the Matlab optimization toolbox. This function was utilized in this study to acquire the local weights where the objective function and the constraints have different formats based on the matrices' sizes. For a (n x n) comparison matrix, there are (n + 1) variables representing n local weights and a consistency index. Table 2 illustrates a fuzzified pairwise comparison matrix and the calculated weights, for one respondent, regarding the capability of the NDT alternatives to detect steel corrosion. For instance, each cell in the matrix has three values that reflect the lower, most probable, and upper values obtained from the fuzzification process.

Table 2: Pair-wise comparison among capability to detect steel corrosion

	IE	PV	GPR	IRT	HCP	Weights
IE	1,1,1	1,1,1	1/6,1/5,1/4	1,1,1	1/8,1/7,1/6	0.07
PV	1,1,1	1,1,1	1/6,1/5,1/4	1,1,1	1/8,1/7,1/6	0.07
GPR	4,5,6	4,5,6	1,1,1	4,5,6	5/12,5/7,5/2	0.33
IR	1,1,1	1,1,1	1/6,1/5,1/4	1,1,1	1/8,1/7,1/6	0.07
HCP	6,7,8	6,7,8	2/5,7/5,12/5	6,7,,8	1,1,1	0.46

6. EVALUATION OF NDT METHODS

Utilizing the procedure explained in section 5, the local weights were obtained for all participants' fuzzified pairwise comparisons, and then the calculated weights were averaged to obtain the final local weights for the main performance criteria, sub-criteria and NDT alternatives as per the developed hierarchy. The obtained weights were analyzed in order to check for unrealistic responses. The percent difference between the relative weights obtained from each of the gathered responses and the average weight was calculated. As a result, two of the questionnaires were discarded due to the high percent difference. The final global weights for the sub-criteria were obtained by multiplying the weights of the main performance criteria by the sub-criteria local weights. The final score for each NDT alternative was obtained by summing the results of multiplying the weights of each method by the global weights of all sub-criteria. Table 3 illustrates all calculated weights and the overall score values of the evaluated NDT technologies. It can be observed from Table 3 that the accuracy of the information provided by the NDT technologies attained the highest weight of 48%, followed by the capability of detecting defects with a weight of 26%. The cost of equipment, data collection and analysis obtained 12%, while speed of data collection and interpretation, and the simplicity of using the methods achieved weights of 8% and 6%, respectively.

Table 3: Results of comparison weights and final ranking of NDT techniques

Main Criteria	Pair-Wise Comparison Weight	Weights - FAHP Sub-Criteria	Weight	NDT Alternatives IE	PV	GPR	IR	HCP
CAPABILITY	0.26	Delamination	0.08	0.26	0.22	0.07	0.38	0.07
		Internal Cracking	0.05	0.26	0.22	0.07	0.38	0.07
		Steel Corrosion	0.13	0.07	0.07	0.34	0.07	0.45
SPEED	0.08	Automation	0.02	0.21	0.21	0.21	0.21	0.16
		Data Collection	0.03	0.15	0.15	0.29	0.29	0.12
		Data Analysis	0.03	0.15	0.15	0.20	0.20	0.30
SIMPLICITY	0.06	Environment & Traffic	0.01	0.24	0.24	0.23	0.11	0.18
		Experience Operator	0.03	0.20	0.20	0.20	0.20	0.20
		Experience Analyser	0.03	0.20	0.20	0.20	0.20	0.20
ACCURACY	0.48	Defect's Location	0.20	0.15	0.09	0.27	0.27	0.22
		Defect's Depth	0.07	0.25	0.06	0.30	0.10	0.29
		Defect's Severity	0.20	0.13	0.09	0.28	0.22	0.28
COST	0.12	Equipment	0.02	0.13	0.13	0.21	0.19	0.34
		Data Collection	0.04	0.11	0.11	0.23	0.21	0.33
		Data Analysis	0.06	0.12	0.12	0.22	0.21	0.33
SUM	1.00		1.00					
		Total Score		0.16	0.12	0.24	0.22	0.26

The overall ranking of the technologies from the perspectives of capability, speed, simplicity, accuracy, and cost are illustrated in Figure 4. The technologies were ranked from high to low, indicating that HCP is the most preferable technology as chosen by the participating experts, while GPR ranked second and IR third. It should be noted that HCP is the most commonly used method. It is currently regarded by experts in the industry and hence, obtained the highest score. The high score of the GPR and IR methods indicates that there is a potential to increase the use of these technologies for detecting deterioration in concrete bridge decks. This is in line with a recent report of the second Strategic Highway Research Program (SHRP 2) where a similar comparative analysis was conducted. Gucunski et al., (2013) concluded in their report that GPR is currently the top technology for detecting and characterizing deterioration in concrete decks. Dinh et al., (2015) compared NDT techniques based on different technical criteria and also reported that GPR appears to be the most appropriate NDE technology for inspection of concrete bridge decks.

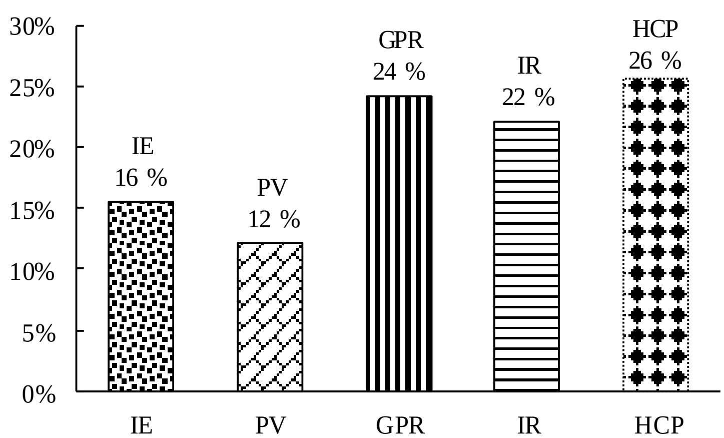

Figure 4: Ranking NDT techniques for detecting subsurface defects in concrete bridge decks.

7. DISCUSSION

The NDT technologies are significantly different in terms of the selected performance parameters. The comparison of individual NDE techniques with respect to the main performance criteria is illustrated in Figure 5. The HCP method obtained the highest score in terms of the capability and cost parameters, while GPR obtained the highest score in terms of accuracy and simplicity. Both GPR and IR obtained the highest scores in terms of the speed parameter. With respect to the detection of a certain type of defects, the preferable two technologies that obtained higher scores for detecting delamination and cracking are the IR and IE methods, while HCP and GPR are the two preferable technologies that have higher potential for corrosion detection. Speed of data collection is an important factor for transportation agencies because of the cost of traffic control and losses and inconveniences associated with traffic interruptions. The GPR and IR methods obtained the highest data collection scores as they are the fastest technologies on bridge decks. All technologies obtained equality score towards the importance of employing experienced operators and analyzers. As the IR technology requires clear skies, mild wind, dry concrete surface, and intense solar radiation to achieve the heat-flow conditions needed to detect the presence of defects, the technology obtained the lowest score towards the environment requirement parameter. The results also indicated that GPR and IR methods have the highest potential to detect a defect's location, while HCP and GPR have the highest potential to detect a defect's depth and severity. With respect to the cost, the survey result indicates that the HCP method has the lowest equipment and data collection cost, and thus is more preferable over the other technologies, while IE and PV obtained the lowest scores, indicating their relatively high cost.

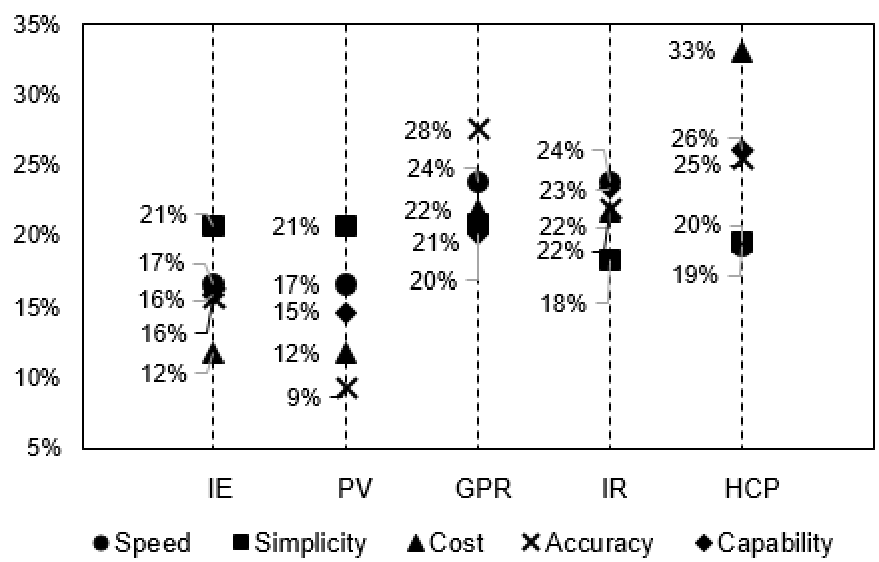

Figure 5: Comparison of NDT technologies with respect to the main performance criteria.

The different technologies have advantages and limitations. For example, while the IR method is applicable for concrete decks with and without asphalt overlays, its information on depth or thickness of defects depends on the environment. The GPR testing requires the presence of moisture in cracks and delamination areas, while the presence of congested reinforcement can prevent signal penetration. HCP limitations include difficult interpretation due to numerous material properties that can influence measurements. Moreover, HCP does not provide quantitative information on the corrosion rate. Inadequate receiver contact during IE and PV testing can give inaccurate and false measurements. In order to increase the accuracy of overall condition assessment of a bridge deck, two or more NDE methods can be integrated to allow the identification of several damage states. For example, the FHWA has recently developed the RABIT bridge deck assessment tool, which contains a panoramic camera, high-definition imaging, electrical resistivity, impact echo and ultrasonic surface waves, GPR, and GPS.

The decision on which technology to select for a specific job and which equipment to acquire depends primarily on the type of deterioration representing the highest concern to the transportation agency and the degree of deterioration details required. Ideally, agencies should have access to at least three of the five technologies explored herein. Selection of the most appropriate NDT technique should be accompanied by a comprehensive cost-benefit analysis. However, (1) if delamination is of greatest concern and is guiding agency decisions, IR or IE with a higher degree of automation are recommended as the NDT technologies of choice; (2) if corrosion is the deterioration of greatest concern, GPR is recommended as the NDT technology of choice; and (3) if the objective of the agency is to obtain the overall condition assessment of many bridges as the case of bridge evaluation in the network level , combined assessment using GPR and IR technologies are recommended because of their high speed and ability to identify corrosion and delamination with relatively high accuracy.

8. CONCLUDING REMARKS

This study attempts to motivate transportation agencies to incorporate NDE techniques into their bridge inspection procedures. The use of NDE methods depends on several factors, including the ability to accurately detect deterioration conditions. Some conclusions were drawn regarding the NDT technologies investigated as follows: (1) HCP is the most commonly utilized technology in concrete bridge inspection, obtaining the highest ranking in this study, yet it has several drawbacks; (2) GPR and IR are promising techniques being the fastest methods. Generally, GPR possesses high detection capability for different defect types, but is dependent on the antenna type for resolution and minimum detection depth. Moreover, IR can possibly have real-time results, but its ability to detect deep defects is controlled by environmental conditions; (3) the IE and PV methods are time consuming and thus obtained the overall lowest ranking due to the requirement of many testing points. Also, testing rough concrete surfaces using these technologies could affect the establishment of low contact times necessary to detect small and shallow defects; (4) NDT methods can be applied alone to evaluate certain aspects of concrete bridges, or can be combined to cover a wider range of testing capabilities in a complementary manner; (5) there is an urgent need to upgrade existing BMSs to incorporate recent research in the NDT field; and (6) fully automated data collection and interpretation analysis seems to be the primary need for further research.

REFERENCES

Bhattacharyya, R., Kumar, P. and Kar, S. (2011). “Fuzzy R&D portfolio selection of interdependent projects.” *J. Computers and Mathematics with Applications*, Vol. 62, pp: 3857-3870.

Chang, P. T., and Lee, J. H. (2012). “A fuzzy DEA and knapsack formulation integrated model for project selection.” *J. Computers and Operations Research*, Vol. 39, pp: 112–125.

Dinh, K., Zayed, T., Romero, F., and Tarussov, A. (2015). “Method for Analyzing Time-Series GPR Data of Concrete Bridge Decks.” J. Bridge Engineering, Vol. 20 (6) pp: 1-8.

Gucunski, N., Imani, A., Romero, F., Nazarian, S., Yuan, D., Wiggenhauser, H., Shokouhi, P., Taffe, A., and Kutrubes, D. (2013). “Nondestructive testing to identify concrete bridge deck deterioration.” *92nd. Annual Meeting, Transportation Research Board,* Washington D.C. SHRP 2 Report, 96 p.

Gucunski, N., and Nazarian, S. (2010). “Material Characterization and Condition Assessment of Reinforced Concrete Bridge Decks by Complementary NDE Technologies.” *Proceeding of Structures Congress*, Orlando, Florida, United States, pp: 429-439.

Huang, C., Chu, P., and Chiang, Y. (2008). “A fuzzy AHP application in government-sponsored R&D project selection.” *The Intern. J. Management Science*, Vol. 36, pp: 1038-1052.

Huo, L., Lan, J., and Wang, Z. (2011). "New parametric prioritization methods for an analytical hierarchy process based on a pairwise comparison matrix." *J. Mathematics and Computer Modeling*, Vol. 54 (11-12), pp: 2736-49.

Mikhailov, L. (2004). "Group prioritization in the AHP by fuzzy preference programming method." *J. Computers and Operations Research*, Vol. 31 (2), pp: 293-301.

Penttala, V. (2009). “*Causes and mechanisms of deterioration in reinforced concrete*.” Book, Publisher: Woodhead Publishing Limited, CRC Press, 323 p.

Saaty. (1980). "*The analytic hierarchy process: Planning, Priority Setting and Resource Allocation*." Book, Publisher: McGraw-Hill, New York, 237 p.

Sasmal, S., and Ramanjaneyulu, K. (2008). “Condition evaluation of existing reinforced concrete bridges using fuzzy based analytic hierarchy approach.” *J. Expert Systems with Applications*, Vol. 35 (3), pp: 1430-1443.

Yehia S., Abudayyeh O., Nabulsi S., and Abdelqader, I. (2007). “Detection of Common Defects in Concrete Bridge Decks using Non-destructive Evaluation Techniques.” *J. Bridge Engineering*, Vol. 12 (2), pp: 215-225.

Zadeh, L. A. (1965). “*Fuzzy sets. Information and Control*.” Report No. 64, pp: 338-353.