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Abstract

To ensure the economic development of a country, preservation of the existing assets is recognized as an important attribute, in addition to the development of new infrastructure. Highways and bridges constitute a major portion of the widely spread network of transportation infrastructure across the globe. For long-lasting performance of these assets, their systematic management including performance assessment, determination of Maintenance and Rehabilitation (M&R) needs, prioritization of pavements, and optimization of resources is required which collectively create Pavement Management Systems (PMS). On similar grounds, Bridge Management Systems (BMS) have been devised to facilitate necessities encountered in bridges. However, the pre-requisite to the efficacious implementation of each of these activities is a quick and reliable condition assessment, over regular durations. Non-destructive Testing (NDT) methods offer a key means to the condition evaluation in a fast, efficient, and accurate manner with no harm to the structure. Undoubtedly there is growing recognition for the use of NDT methods in condition evaluation of pavements as well as bridge decks, however, their usage is not widespread in developing countries like India. Challenges faced in widespread usage of NDT technologies like high equipment cost, lack of technical expertise, complex data analysis procedures, etc., pose a major limitation in regularly monitoring structural health of pavements. Accordingly, the present framework of PMS is largely dependent on subjective assessment procedures for M&R decision-making activities which may contain ambiguity, vagueness and uncertainty due to varying opinions of decision-makers.

Based on the facts mentioned above, the present study identifies Infrared Thermography (IRT) as one of the rapid assessment NDT technology, capable of covering large areas with great ease of use. However, due to the lack of quantitative analysis approaches for IRT, the study attempts to develop novel and robust IRT data analysis procedures for both asphalt pavements and bridge decks. Decision-support model frameworks using various Multi-Criteria Decision-Making (MCDM) techniques and computational intelligence tools have also been devised to upgrade current PMS. A conscious attempt is made to develop model frameworks, which are demonstrated using actual field data and inculcate parameters from different domains, viz., structural performance, functional performance, subgrade soil, and environment-related. The frameworks

also utilizes the quantification of experience-based knowledge of decision-makers gained over several years.

The study primarily focuses on: (i) demonstrating and developing systematic approach for utilizing IRT for delamination detection and Ground-Penetrating Radar (GPR) for anomaly detection in asphalt pavements; (ii) demonstrating and developing systematic approach for utilizing IRT for delamination detection in concrete bridge decks and emphasizing the need for combination of methods by demonstrating application of GPR adding merits and complimenting IRT testing; (iii) devising approaches to support decision-making on M&R expenditures and sustainability prospects; and (iv) offering easy and intelligent approach for structural performance prediction modeling of pavements.

For exploring the potential of IRT and GPR in delamination, anomaly, and internal flaw detection under asphalt pavements, and bridge decks; two in-situ testing facilities: asphalt pavement test section and concrete bridge deck slab, are developed and simulated with artificial defects; as discussed in Chapter 3. The NDT testing details, novel data analysis approaches developed using MATLAB, presentation of results, and estimation of ideal testing durations for Indian conditions along with summary of their performance are discussed in Chapters 4 and 5, for asphalt pavement test section and concrete bridge deck slab, respectively.

Field investigations conducted under uncontrolled conditions using Heavy Weight Deflectometer (HWD), GPR, and visual surveys for demonstration of various model frameworks are presented in Chapter 6. This real field data is used to demonstrate the development of various data-driven model frameworks for decision-support system utilizing MCDM techniques namely, analytic hierarchy process, fuzzy inference system, Buckley's analytic hierarchy process, and Cheng's entropy-based fuzzy analytic hierarchy process; in addition to integrated SWOT-fuzzy analytic hierarchy process and discussed in Chapter 7. The approaches discuss the development of composite condition indicator and method to prioritize the pavement sections for M&R to optimally allocate resources. The superiority of fuzzy-based techniques is evident from the results. The SWOT-fuzzy based approach tries to assess the potential implications of pavement M&R activities and assists in holistic decision-making exercises while consideration of sustainability prospects. The formulation of structural condition prediction models based on computationally intelligent artificial neural networks are presented in Chapter 8, which also validates the superiority of intelligent approaches over non-intelligent models.

The IRT tests conducted in this thesis explores their potential to detect delamination in asphalt pavements and bridge decks, and derives the field inspection time zones for Indian conditions using this particular NDT technology. The proposed data analysis methodologies offer quantitative interpretation of thermal images rather than purely judging them on subjective basis. These attempts would be greatly beneficial to the transportation agencies of developing countries like India, to reaffirm the practical adequateness of using IRT inspections for quick and economical delamination detection. The additional NDT tests conducted using GPR corroborate the expediency of performing combination of tests, particularly on bridge decks.

The decision-support methodologies proposed in this work which incorporate advanced fuzzy MCDM techniques and SWOT model frameworks, enable the concerned decision-makers to objectively justify budget requirements for M&R and obtain the funding from agencies. With the introduction of prioritization approaches, engineers and managers are enabled to identify those pavement sections that need attention and hence allocate resources judiciously. Especially in developing countries where budgetary constraints do not allow highway agencies to preserve entire network of pavements using optimal preservation strategy, the management system strives to achieve the maximum benefits through prioritization. Applicability and effectiveness along with uniqueness of the proposed methodological frameworks is demonstrated by employing a case study of airfield pavements at an international airport. The results from the case study clearly indicate that all the developed models are practical, robust, time and cost-effective, easily understandable by the stakeholders (policy makers and concerned authorities involved in decision-making), and gives importance to sustainability aspects of M&R activities as well. They are also able to very well incorporate the randomness and uncertainty associated with pavement M&R decision-making processes. These aspects received less attention in earlier studies available in the literature.

The reliable correlations developed using the tools of computational intelligence are expected to popularize the implications of structural adequacy factors in pavement M&R decision-making and ease the work of transportation agencies in obtaining structural condition data. The neural network

models are favorable to be used in developing countries since they are flexible with the addition/modification of data and work well even with the limited data availability that can be easily collected during routine inspection practices.

Considering the fact that the Government of India is spending tremendous funds on development and improvement of pavement infrastructure, the work undertaken in this thesis finds wide applicability in judicious and optimal utilization of funds and resources. The overall conclusions presented in Chapter 9 with correspondence to the aim of the study as discussed in Chapter 1, highlight the need of employing scientific approach in pavement evaluation, monitoring and management studies. The work also assists concerned policy makers for formulating sustainable policies to enhance overall benefits of maintenance projects. Thus, it is expected that, the study performed herein can be considered as a crucial step in improvising present-day management systems of developing countries amidst limited resources and provide basis to deepen the research work in this direction.

Keywords: Pavement condition assessment, Pavement management systems, Non-destructive testing, Infrared thermography, Falling weight deflectometer, Fuzzy AHP, SWOT, Artificial neural networks

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List of abbreviations

Abbreviation	Description
2D	Two-Dimensional
3D	Three-Dimensional
ACN	Aircraft Classification Number
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
ANN	Artificial Neural Networks
ASTM	American Society for Testing and Materials
BCI	Base Curvature Index
BMS	Bridge Management System
BP	Back-Propagation
BW	Body Waves
CBR	California Bearing Ratio
DBP	Deflection Basin Parameters
ER	Electrical Resistivity
EM	Electromagnetic
ET	Exit taxiways
FAA	Federal Aviation Administration
FAHP	Fuzzy Analytic Hierarchy Process
FIS	Fuzzy Inference System
FWA	Fuzzy Weighted Average
FWD	Falling Weight Deflectometer
GA	Genetic Algorithms
GoI	Government of India
GPM	Galvanometric Pulse Measurement
GPS	Global Positioning System
GPR	Ground-Penetrating Radar
HCP	Half-Cell Potential
HDM	Highway Development and Management
HMA	Hot-Mix Asphalt
HWD	Heavy Weight Deflectometer
ICAO	International Civil Aviation Organization
IE	Impact Echo
IR	Impulse Response
IRI	International Roughness Index
IRT	Infrared Thermography
LWD	Light Weight Deflectometer
MAE	Mean Absolute Error

MAPE	Mean Absolute Percentage Error
MASW	Multichannel Analysis of Surface Waves
MCDM	Multi-Criteria Decision-Making
MDD	Maximum Dry Density
MoRTH	Ministry of Road Transport and Highways
M&R	Maintenance and Rehabilitation
MR&R	Maintenance, Rehabilitation and Replacement
MSE	Mean Square Error
NDT	Non-Destructive Testing
OT	Opportunity-Threat
OTW	Opportunity-Threat-Weakness
PCC	Plain Cement Concrete
PCI	Pavement Condition Index
PCN	Pavement Classification Number
PMGSY	Pradhan Mantri Gram Sadak Yojana
PMS	Pavement Management Systems
PSI	Present Serviceability Index
PSPA	Portable Seismic Property Analyzer
PSR	Present Serviceability Rating
RAP	Reclaimed Asphalt Pavement
RAS	Reclaimed Asphalt Shingles
RCA	Reclaimed Concrete Aggregates
RCC	Reinforced Cement Concrete
RMSE	Root Mean Squared Error
RN	Ride Number
SASW	Spectral Analysis of Surface Waves
SCI	Surface Curvature Index
SO	Strength-Opportunity
SOWT	Strength-Opportunity-Weakness-Threat
SSE	Sum Square Error
SW	Surface Waves
SWOT	Strength-Weakness-Opportunity-Threat
UPE	Ultrasonic Pulse Echo
USW	Ultrasonic Surface Waves
WO	Weakness-Opportunity

List of notations

Notation	Description
A	Aluminum plate
A_0	Amplitude of surface reflection
Ai	Alternatives
A_p	Amplitude of incident GPR wave
$\tilde{A}$	Fuzzy judgement matrix
α	Confidence interval
B	Bentonite slurry
C	Cast-iron plate
C1,C2,…,C5	Number of criteria
CI	Hollow cast-iron pipe
CL	Cast-iron L-section
CR	Corroded rebars
D	Delamination detected
DL	Delamination
D_i	Geophone number with reference to centre
DW	Dust along the wheel paths
E_i	Entropy value
FB	Full bond
F_j	Fuzzy utility functions
F(x,y)	Value of each element of binarized image
G	Grease
λ	Index of optimism
i	Number of input nodes in ANN model
L3, L6	Longitudinal profile 3m and 6m to the left of runway centreline
L_a	Thickness of asphalt layer
L_b	Thickness of base layer
L_t	Total thickness of pavement
m	Neurons in the first hidden layer
$\widetilde{m_1}$	Trapezoidal fuzzy number
n	Neurons in the second hidden layer
ND	Delamination not detected
O_i	Observed values of any data point
p	Neurons in the i^{th} hidden layer
P	Hollow PVC pipe
P_i	Predicted values of any data point
P_{ij}	Grayscale intensity of the pixel
PB	Partial bond

PD	Delamination partially detected
PO	Polythene
R3, R6	Longitudinal profile 3m and 6m to the right of runway centreline
S	Sand
S1,S2,…,S12	250 m long runway pavement sections
S_{ji}	Performance scores
SP	Hollow steel pipe
Δt	Thermal contrast
(t_1,t_2,t_3)	Fuzzy triplet
T_a	Atmospheric temperature
t_d	Temperature of damaged area
T_{del}	Lowest temperature of delaminated area
T_{ij}	Temperature at the point corresponding to the pixel in the i^{th} row and j^{th} column
T_l	Calibrated minimum temperature
T_h	Calibrated maximum temperature
T_{max}	Maximum temperature in the thermal image
T_{min}	Minimum temperature in the thermal image
t_s	Temperature of sound area
T_s	Asphalt pavement surface temperature
$T(x,y)$	Pixel value of temperature
$\tilde{T}$	Total fuzzy judgement matrix
$\hat{T}$	Precise judgement matrix
μ	Membership function
V	Voids
VC	Vertical cracks
W	Wood block
$\tilde{W}$	Fuzzy subjective weight vector
w_i	Fuzzy weights of criteria
X	Input decision variables to ANN model
x_i	i^{th} data point of the ANN input dataset
x_{max}	Maximum values of the ANN input dataset
x_{min}	Minimum values of the ANN input dataset
$\tilde{X}, \tilde{Y}$	Fuzzy numbers
y	Net input to the hidden layer neuron
z	Output from the hidden layer neuron after sigmoid function