Chapter 1
Introduction

1.1. Introduction

A well-planned and efficient transportation system having highways, airfield pavements, and bridges as its integral part plays a pivotal role in the sustained socio-economic development of a country. A well-developed network of pavements in all these domains ensures comfort and safety to the users but demand huge investments. India has the second-largest road infrastructure in the world that accounts for 5.48 million km of roads to transport 85% passenger and 65% freight traffic. The transportation sector is one of the fastest-growing sectors in the country, both in terms of new construction, as well as the improvement of existing networks. With 10,855 km of highways constructed in the previous financial year and a set target of 12,000 km national highway construction in the present fiscal year, the aim is to provide the nation with 65,000 km of national highways at the cost of Rs 5.35 lakh crore by 2022 (Economic Times, 2019). Government of India (GoI) and the Ministry of Road Transport and Highways (MoRTH) have undertaken many initiatives and continue to do so by investing a substantial amount of money for the development of the Indian road sector. Under the Union Budget 2020-21, GoI sanctioned Rs. 91,823 crore under MoRTH. The ministry allocated part of this fund towards the maintenance of the road sector (Rs. 3,150 crores) and Rs. 280 crore for road transport and safety. For rural areas also, fund of Rs.19,500 crore was allocated under the budget of 2020-21, with approval for the launch of Phase-III of Pradhan Mantri Gram Sadak Yojana (PMGSY) (IBEF, 2020).

In spite of massive investments of funds for the construction and maintenance of this extensive network, multifold challenges are faced by highway agencies. One of the greatest difficulties is to maintain the constructed infrastructure and safeguard year-round, high-quality standards. However, soon after the completion of construction, the infrastructure gets exposed to various detrimental agents. Adverse impacts of a wide variety of vehicular loading and weather conditions are significant contributors to the process of deterioration. In addition to this, improper design, use of low-quality construction material, poor construction and maintenance practices, and inadequate drainage results in premature failure of the pavements. The situation is more severe in the case of

airfield pavements and bridge decks. Airfield pavements are subjected to heavier loads of aircraft and hence, prone to expeditious deterioration whereas bridges are susceptible to abrupt collapse of the structure (Destafney, 1985). The rate of deterioration is slow during the initial stages after construction, which increases rapidly as time progresses. The continual degradation gives rise to a number of defects, and many of them may not be apparently visible but greatly reduce the structural capacity of structures in which they occur. These hidden subsurface defects pose a higher risk and threat to the safety of citizens since the level of their progression is difficult to assess, and they generally cause sudden failure of the structure taking a huge account of life and property.

One of the prominent and commonly occurring internal defect in Hot-Mix Asphalt (HMA) pavements, as well as bridge decks which adversely affects their structural capacity, is delamination. Loss of adhesion between HMA layers occurs due to the phenomenon of debonding and gives rise to delamination. Therefore, it may be noted that for asphalt pavement layers, the terms delamination and debonding have been used interchangeably in the thesis. Debonding becomes apparent in the form of slippage or half-moon shaped cracks with ends pointing in the direction of traffic movement. Slippage failures at highways, urban road stop-and-go intersections have reported such cracks due to vehicle manoeuvres (Asphalt Institute, 2009; Chen, 2010; FAA, 2014a; IRC 82, 1982). The impact is more critical on airfield pavements, particularly in the areas undergoing large horizontal thrust of aircraft during braking, turning or take-off operations, such as at runways and exit taxiways (Bognacki et al., 2007). Many serious mishaps have occurred due to the same (Hachiya & Sato, 1997). One such failure occurred on the runway of Nagoya Airport in Japan (Tsubokawa et al., 2007). Few construction practices like multiple thin lift pavement construction in order to achieve better compaction, also aggravate the occurrence of delamination by providing more interfaces that may loose bond under the impact of high shear forces. Poor drainage and wet weather construction have resulted in the development of crescent-shaped cracks and debonding of asphalt overlays at runways and taxiways (Horak et al., 2009). Exhausts and leakage of jet turbine fluids can also be held responsible for enhancing these problems at airfield pavements. In a similar way, delamination between reinforcement bars and surrounding concrete occurring in Reinforced Cement Concrete (RCC) bridge decks is among dangerous deterioration types due to its invisibility during visual surveys and leads to potential spalls. Other commonly found internal defects of RCC bridge decks include corrosion in rebars and vertical cracks. Local failures in HMA layers may also occur due to underground anomalies. In the absence of timely

maintenance measures, the severity of deterioration increases and demand arises for more funds to address the problems. As a result, deteriorating and ageing pavement and bridge infrastructure necessitates its systematic maintenance and not solely management. This compels reliable and frequent monitoring of their health conditions to govern Maintenance and Rehabilitation (M&R) strategy in the form of preventive or corrective maintenance, rehabilitation, recycling, or reconstruction. However, M&R of any pavement infrastructure is a costly affair; hence, their successful implementation should undergo through a series of decision-making exercises pertaining to M&R at various levels; the pre-requisite for each sound decision is true knowledge about the existing condition. Therefore, adopting any M&R measure without thoroughly investigating the current condition might lead to wrong decisions and may prove uneconomical and ineffective in the long run. Functional condition assessment is relatively easier to perform and is a commonly adopted practice. The real challenge lies in the reliable evaluation of structural health, and assessment of delamination as its imperative component.

Conventional and existing field procedures for in-situ evaluation of delamination are rather limited. Coring practices are reliable to measure the depth and severity of delamination but only when they appear as surface distress. Also, the methods are essentially destructive, which makes them ineffective for long lengths of pavements. Therefore, the cause of concern for highway agencies is to become capable of detecting delamination along with its extent, during the initial stages of occurrence itself to avoid distresses appearing visually while causing a substantial loss in structural integrity. The detectability of any technology is its ability to accurately locate a defect without reporting a sound location as defective. Recent advances in Non-Destructive Testing (NDT) techniques minimize the need for destructive testing and offer a valuable tool to evaluate existing or new pavement infrastructure for quality control during construction processes and structural condition assessment, post-construction stages. The testing process that occurs under actual field conditions causes no material disturbance, minimum disruption to traffic, and minimizes the need for destructive tests in its conjunction. Being relatively quick to execute, NDT devices are adequate for regular monitoring purposes that would help in planning, optimizing, and implementing periodical M&R activities, even during the early stages of deterioration. Therefore, over half of the costs can be saved, and a long period of traffic diversions or closures can be avoided (Shahin, 2005). As identified from the literature, some of the NDT devices showing potential for delamination detection are Ground-Penetrating Radar (GPR), Infrared Thermography

(IRT), mechanical wave-based methods like Impact Echo (IE), Impulse Response (IR), Spectral Analysis of Surface Waves (SASW), and deflection methods such as Falling Weight Deflectometer (FWD). Besides detectability, uncertainties such as availability and cost of equipment, speed of data collection, ease of data analysis, and depth of detection differ for each one of them and limit their usage.

In developing countries like India, despite the superiority of NDT tools over conventional procedures for structural health assessment of pavements, use of NDT is not very popular and restricted to research purposes. The in-field application of NDT is usually limited to the estimation of pavement layer thickness, layer moduli and overlay design. Even for these applications, the availability of devices is scarce. High equipment cost, technical immaturity, ineffective use of results, and lack of appreciation of the underlying skill, may be cited as a few reasons to limit their usage on a broad scale. Efforts are needed to widespread the use of NDT by demonstrating their tangible merits over conventional techniques, and devising more objective data analysis approaches. NDT are relatively new technologies to implement; hence the expertise on their usage is poor. In such cases, to acquire the understanding and technical cognizance, conducting their in-field studies under controlled conditions would be more effective rather than their direct implementation in the real field. Infrared thermography, one of the NDT technology, is capable of delivering quick results. Although quite successful in concrete structures, its potential to detect delamination in asphalt pavements is not fully explored. Due to several merits of being quick, capable of covering large areas, and ease of collecting data, it has the possibility to become a popular tool by highway agencies to monitor structural deficiency of delamination. Research is needed to deliver quantitative estimates of the thermal images rather than mere qualitative results, to foster a more judicious analysis of pavement conditions. In bridge decks as well, promoting the use of IRT would eliminate obsolete bridge assessment methods such as chaining and hammer sounding. Such quick assessment procedures will lead to (1) better allocation of resources, (2) efficient decision-making, and (3) reduced traffic interruption caused by slow and less effective inspection approaches.

The decision-problem after perceiving the pavement condition from NDT tools is to select the right pavement sections for treatment i.e., to prioritize the sections at a given time for implementation of appropriate M&R and justify budget requests to funding agencies using an

objective process. It is a complex decision-making problem due to the contribution of multiple and conflicting criteria in the assessment. The problem is frequently confronted by transportation administrators, especially in developing countries since mostly the funds required to perform necessary repairs is larger than the available budget. Moreover, the requirement of the amount keeps rising with new construction activities. The gradual deterioration of the infrastructure over the years clubbed with inability in timely M&R owing to a limited budget, material shortage, environmental restrictions, etc., worsens the situation to the extent that M&R may take priority over other highway projects. Implementing M&R during this phase incurs higher costs, but it is imperative in the light of its significant national interest. In order to mitigate the gap between funds needed and funds available, careful planning and intelligent policies are required. Pavement Management Systems (PMS) can help the decision-makers to optimally allocate available funds for which a number of comprehensive packages are also available, but the majority of them require huge databases (Sandra, 2007). The PMS vary greatly from one transportation agency to another, and the management decisions are generally focused on aspects related to technicality, economy, and safety. Nowadays transportation sectors worldwide are increasingly paying more attention to the impact of their decisions on the sustainability aspect as well. However, none of the studies conducted earlier has tried to inculcate the impact and analysis of strength, weakness, opportunity, and threats of pavement monitoring and maintenance projects. Since the cost of deteriorating infrastructure is a quite expensive operational expense, hence prior knowledge about the potential impacts of such projects would be beneficial. Therefore, in order to inculcate all these factors, need arises to devise a meticulous, effective, economical and flexible decision-support system that could assist in taking organized maintenance decisions for operation of a "greener" highway system.

Additional decision problem generally encountered in developing countries while selecting the type of M&R arises due to the consideration of only functional parameters of pavements and disregarding its structural aspects. This happens as a result of the ease of collecting functional condition data but the absence of structural condition assessment obscures the accurate portrayal of pavement health and may elicit feeble M&R choices. Negligence of structural aspects at this level has severe consequences at later stages when the cost of M&R would become multifold. Despite the recommendations on the use of FWD are high for the routine inspection of the structural integrity of pavements, it has seen slow adoption in India. A few reasons are identified that limit its widespread and frequent use. Due to high initial cost, it has limited availability in

India, hence every time the equipment needs to be transported at the location for testing that may not always be economical and feasible. Moreover, the data analysis procedure is rigorous and requires technical proficiency with the prerequisite of accurate layer thickness measurements that demands the use of another NDT tool such as GPR, or coring practices. Since GPR is not so commonly used in India and coring is a time-consuming and labour-intensive process, the entire process of adopting the frequent use of FWD becomes cumbersome. On the contrary, visual inspection and identification of functional compatibility of pavements are easier. Hence, approach delivering quick estimation of structural inadequacy is required along with the ease of its implementation to foster the usage of structural parameters in M&R decision-making. The scope of artificial intelligence owing to its inherent advantages, in this regard, needs to be further explored.

1.2. Research objectives

The research work intends to develop a systems approach for optimally evaluating and maintaining the pavement network by judicious and effective utilization of available funds. It would aid in updating and improving the existing PMS within India. The study also aims to devise more holistic decision-making approach with long-term goals by considering the alarming aspects of environment and energy, to serve as an added advantage with its implication of a sustainable future, rather than merely satisfying the requirement of transporting goods and passengers. Following objectives have been set to achieve the goal:

1. Review and identify main asphalt pavement and RCC bridge deck condition indicators.
2. Exploration of best practices of NDT for delamination detection in asphalt pavements and bridge decks through extensive literature review.
3. Critically review available pavement prioritization and prediction modeling techniques.
4. Evaluate the potential of IRT for delamination detection in asphalt pavements and RCC bridge decks and estimate their ideal field inspection time zones for Indian conditions.
5. Develop novel methodologies for post-processing of thermal images quantitatively.
6. Assess the utility of IRT and explore merits of coupled use of IRT-GPR for anomaly identification in asphalt pavements and other internal flaws in RCC bridge decks.

7. Devise objective and data-driven approaches to justify M&R needs and select right pavement sections for M&R implementation amidst limited funds by prioritizing using soft-computing techniques.
8. Enabling highway agencies to break ties between identical maintenance strategies by prioritizing the pavement sections rationally.
9. Develop a SWOT-based decision-making approach for a strategic framework of pavement maintenance, rehabilitation and usage.
10. Devise methodology for quick estimation of structural condition of pavements to promote their usage while taking appropriate M&R decisions/strategies, using computational intelligence approach.

1.3. Scope of the present study

The present study initially focuses on the identification of various non-destructive testing technologies showing the potential for detection of structural deficiency in terms of delamination and underground anomalies. The techniques are assessed on the basis of parameters such as accuracy, speed, ease of data analysis, and depth achieved by taking references from previous studies. Infrared thermography technique manifesting potential of quick delamination detectability is chosen. Its utility is assessed by conducting tests on in-situ fabricated asphalt pavement and RCC bridge deck induced with artificial delaminations. Innovative methodologies for quantitative post-processing of thermal images have been developed using MATLAB, and field inspection time zones have been interpreted for Indian conditions. A combination of IRT and GPR is explored to address the limitations encountered in thermographic inspections.

Furthermore, around the globe, several departments of transportation face major undertakings in the form of ranking and prioritization of pavement infrastructure for M&R. The study aims to find answers of various questions encountered whilst the decision-making processes of pavement M&R.

1. How to justify that M&R are necessary and obtain funding for their implementation?
2. How to choose the right pavement sections for implementation of M&R activities during budgetary constraints?
3. What methods can be used for the rational prioritization of pavement sections to receive M&R?

4. How to assess the potential impacts of M&R projects beforehand in order to safeguard against the negative ones?
5. How to encourage the usage of structural parameters of pavements while M&R decision-making exercises?

Justification for the necessity of M&R and selection of right pavement sections for the same requires the development of an objective process. The condition of pavement sections is represented using a composite index that covers the impact of various parameters from structural, functional, traffic, and environmental domains on pavement health. For prioritization of pavement sections, different approaches based on both subjective Analytic Hierarchy Process (AHP) and objective fuzzy-based soft-computing techniques are developed using multiple decision criteria. Soft-computing techniques such as machine learning, fuzzy logic, and expert systems, are based on solving problems with approximate models and hence handles partial truth, imprecision, and uncertainty in a better way (Fathi et al., 2019). Superiority of fuzzy-based approaches is justified for such complex decision problems. The weights used in the developed approaches are determined from expert opinion surveys. In order to demonstrate the methodology, it was decided to take up the case study on asphalt pavement of a runway.

Further, as already stated, due to considerable money spent in pavement maintenance projects, prior analysis of its probable impacts in future would assist in framing strategic framework and help in developing holistic decisions considering sustainability prospects. The study proposes an innovative approach employing SWOT models with concepts of fuzzy theory, and demonstrated using the same case study of runway. The current condition of runway sections is depicted by cumulatively defining the impact of various parameters using a score or index. The robustness of developed approaches is presented by performing sensitivity analysis. The study area is limited to airfield pavements of an international airport. Field investigations performed using NDT were limited to the use of Heavy Weight Deflectometer (HWD) and GPR along with visual surveys.

Another decision problem of negligence of structural adequacy parameters while pavement M&R decisions is addressed by developing analytical prediction models. Superiority of Artificial Neural Networks (ANN) over multiple linear regression in prediction modeling is depicted by a case study. The data collection was limited to a few selected road stretches covering State Highways in

the Indian state of Rajasthan. Data from various domains covering structural, functional, subgrade soil, and environment was obtained. Various analytical relationships were developed to express structural adequacy parameters of pavements in terms of these different attributes collected at a point of time, and the best network is proposed. In the direction to promote the usage of structural health of pavements while dealing with M&R decision-making, developing analytical prediction models using neural networks has been proposed.

1.4. Organization of the thesis

This thesis consists of nine chapters. The details covered in each of these chapters are described as follows:

Chapter 1 introduces the broad areas of the study undertaken and the need for the various research activities. It also highlights the objectives, scope and details of thesis organization.

Chapter 2 while covering the overview and major components of pavement management systems and bridge management systems, discusses the historical and current practices of various non-destructive testing technologies ideal for delamination detection in asphalt pavements and bridge decks. The advantages and limitations of these methods are also discussed. In addition to this, various pavement prioritization techniques and prediction models are reviewed.

In **Chapter 3,** the development of in-situ asphalt pavement test section, and concrete bridge deck slab is discussed with the details of their planning, designing, and construction activities. These facilities are constructed for the purpose of conducting NDT testing under controlled conditions.

Chapter 4 discusses the details of NDT testing conducted on in-situ asphalt pavement test section for detection of delamination between HMA layers and identification of underground anomalies. A novel methodology is proposed for offering quantitative estimates in post-processing of infrared thermography outcomes, i.e., thermal images.

Chapter 5 deals with the details of NDT testing conducted on fabricated concrete bridge deck slab for detection of various deterioration types particularly delamination, and an innovative data analysis approach developed using MATLAB for infrared thermography results.

Chapter 6 presents the details of field investigation and collection of pavement condition data using NDT testing on airfield pavements, taken as a case study.

In **Chapter 7**, data-driven approaches of decision-making for pavement prioritization using various soft-computing techniques of multi-criteria decision-making have been formulated and compared. The approaches developed are demonstrated using the case study explained in Chapter 6.

Chapter 8 presents the various prediction models using artificial neural networks for estimation of structural adequacy parameters of pavements. The results are also compared with multiple linear regression approach.

Finally, **Chapter 9** of the thesis concludes the study with findings, and highlights the contributions made through the present research. The study proposes easier frameworks for efficient condition monitoring of asphalt pavements and RCC bridge decks; objective prioritization approaches; and intelligent models for structural performance prediction of pavements, keeping in view various governing attributes and sustainability prospects. Future scope of present research work along with the limitations and assumptions has also been enlisted in this chapter.

The objectives set for this research work are quite essential for pavement management systems which are explored further through comprehensive literature review as discussed in subsequent chapter of this thesis work.

1.5. Bibliographical note

Parts of Chapters 3, 4, 6, 7 and 8 appear in the following journal papers:

- Vyas, V., Singh, A. P., Srivastava, A. (2019). Entropy-based fuzzy SWOT decision-making for condition assessment of airfield pavements. *International Journal of Pavement Engineering*, Taylor and Francis, pp. 1-12. https://doi.org/10.1080/10298436.2019.1671590. (I.F. 2.298).

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