Chapter 2
Literature review

2.1. Introduction

Asphalt pavements, new as well as existing ones, are multilayered structures owing to overlaying Hot-Mix Asphalt (HMA) layers. Due to difficulties faced during compaction of thicker HMA lifts, asphalt pavements are generally not constructed in a single lift, and this makes interfaces inevitable between the layers. Therefore, the pavement life depends not only on the properties of individual layers but also on their interface bond. In previous years, the strength of this bond, and hence structural capacity was not given much attention while more emphasis was paid on surface distresses. Accordingly, as the first objective of the study, different domains indicating pavement condition were identified and reviewed. Nevertheless, there were problems reported in the literature due to bond failures at highways as well as airfield pavements (Hachiya & Sato, 1997; Lepert et al., 1992). From about the past two decades focus has been given to the bond condition, and techniques to assess its strength. However, estimation of a poor bond at its early stages is difficult due to its non-visibility that progresses to its premature failure. Best practices of Non-Destructive Testing (NDT) tools have been explored that can perform well in locating the delaminated areas. In accordance with this, studies carried out by various researchers to identify debonding between HMA layers were reviewed. The multiple tools adopted by the researchers to evaluate the same have also been reviewed.

Reinforced concrete bridge decks undergo subsurface delaminations that are indicative of deterioration and active corrosion. Further applications of Infrared Thermography (IRT) have been explored for delamination detection to reveal challenges and uncertainties associated with it, in addition, to discover ideal testing time and image processing methodology. Keeping this in view, the second objective includes a review of bridge management systems, deterioration phenomenon in concrete bridge decks, and studies performed for its evaluation using NDT tools. Review of a variety of test methods has revealed the fact that a combination of methods is recommended for deck evaluation to overcome the limitations of any single NDT.

The discrepancy between funds needed and funds available for maintenance is not unique. Owing to a large network of Indian roads, and being in the developing stage, the country has limited resources. Therefore, to avoid budget shortfalls, and ensure optimized maintenance costs of pavement network, prioritization of pavement sections becomes mandatory rather than a preference. It is not only limited to highways, but applies equally to airfield pavements and low-volume roads as well. Prioritization leads to the logical and optimal distribution of funds and plays an important role in Pavement Management Systems (PMS). Accordingly, pertaining to another objective of the study, various prioritization techniques have been reviewed in detail, with emphasis on fuzzy-based techniques.

Neural networks have been found to be a viable tool for prediction modeling of pavements as ascertained by the review of literature. An easy approach is developed by incorporating Deflection Basin Parameters (DBP) in Artificial Neural Networks (ANN) to avoid frequently undergoing cumbersome test procedures at a network level, to obtain knowledge about the structural condition of pavements, and inculcate their effect during Maintenance and Rehabilitation (M&R) decisions. This is covered as one of the objectives of the research, and literature relevant to modeling techniques and their applications using DBP are reviewed.

The discussion presented herein corroborates that all the objectives form an important part of PMS. Therefore, first of all, PMS and its components are discussed briefly. Furthermore, studies on condition assessment of asphalt pavements and concrete bridge decks, prioritization techniques and prediction modeling are discussed in a concise form.

2.2. Pavement management systems

Pavement management system was first introduced during the late 1960s and early 1970s. It was believed to be a result of a shift from ‘design and build’ concept to ‘maintain and repair’ concept when after investing huge amount in highway construction, the need aroused to preserve the built infrastructure with scarce funds. The situation demanded a more cost-effective approach of utilizing available resources and led to the development of the concept of PMS. A number of researchers, engineers, and government officials worked on developing the first of the management systems. Early PMS relied on planning for a single year based on subjective ratings, and typical characteristics such as current distress, age of pavement, and intensity of heavy vehicles (trucks). Consideration of future pavement conditions, user costs, and life-cycle costs were not employed, and simple priority ranking was used (Kulkarni & Miller, 2003). Since then, the present-day PMS has been continuously evolved in terms of its scope, methodology, and implementation.

Scientists and well-known agencies highlight the purpose of PMS and state a few similar definitions (AASHTO, 2001; FHWA, 1989; Haas et al., 1994; Hudson et al., 1979). Haas et al. (1994) defined PMS as a 'set of tools or methods that assist decision-makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time'. Thus, it can be concluded that PMS aims at strategically managing pavement network within an optimum budget and maximized benefit to serve users with serviceable, and safe pavements. Accordingly, the essential requirements of PMS include adaptability to modify existing models, practicality to consider alternative strategies, efficiency to select an optimum alternative, rational decision-making procedures, and feedback of consequences of decisions (Hudson et al., 1979).

2.2.1. PMS components

On the basis of needs, goals, and objectives of agencies, a PMS should be composed of the following components (Haas et al., 1994; TAC, 2013):

- Data inventory: It requires collecting a broad database including pavement performance data, geometric data, environmental data, historical data, policy and cost-related data.
- Condition assessment: It should include the pavement attributes that should be measured with required equipment, and methods, such as structural adequacy, surface distress, roughness, and friction (NCHRP, 2004).
- Pavement performance prediction models: In order to predict pavement deterioration at any time, and their future condition; deterministic, stochastic, and artificial intelligence models can be used.
- M&R strategies: Various preventive and corrective maintenance alternatives or rehabilitation practices can be employed based on the acceptable limits of the level of pavement deterioration.

- Economic assessment: In the selection of M&R strategies, their economic analysis is performed by methods such as present worth method, benefit-cost ratio, equivalent uniform annual cost method, rate-of-return method, and cost-effectiveness method (Haas et al., 1994; TAC, 2013).
- Prioritization and Optimization: Priority ranking and optimization tends to address the pavement section to be considered first for M&R, the alternative to be utilized for the selected section, and suitability on the application of these alternatives; all within budgetary constraints, and established criteria.

2.3. Condition assessment of asphalt pavements

One of the main components for successful implementation of PMS is the evaluation of the pavement condition. It incorporates the measurement of qualitative and quantitative characteristics of pavements to obtain knowledge about their structural and functional health. Structural condition evaluation comprises of estimating the structural capacity of pavements and may be expressed by surface deflection, the thickness of layers, layer moduli, bond conditions at the layer interfaces or anomaly categorization (Goel & Das, 2008). Functional condition refers to the ability of pavement to perform its function and may be expressed in terms of serviceability, surface distress, and safety. The type of data collected, and its utilization varies with the goals and resources of the individual agencies. Therefore, each one of them generally develops their own guidelines or protocols to collect data in accordance with their needs. A few of these agencies including, AASHTO, ASTM, FHWA, etc., have developed well-established protocols, and standardized methodologies (AASHTO, 2011; ASTM D6433-09, 2009; Miller & Bellinger, 2003).

2.3.1. Serviceability

The concept of serviceability was developed for the judgment by users for whom the pavements are built, and it is mostly indicated by the ride quality. A group of evaluators rate the serviceability of pavement while riding a model passenger car, and it is reported as Present Serviceability Rating (PSR) that is largely qualitative, and subjective. In early efforts for devising objective measurements, these ratings were related to factors representing pavement condition such as roughness, rutting, and cracking. One such relationship defines the Present Serviceability Index (PSI) that is a 0-5 rating system to indicate the ability of pavement to serve traffic (HRB, 1961). It concluded pavement roughness as one of the most significant factors contributing to pavement serviceability. Devices such as roughometers, and profilometers are used to measure roughness. Latest variants of these devices use non-contact sensors, such as laser, ultrasonic, or infrared. In the efforts to quantify pavement roughness universally, International Roughness Index (IRI), and Ride Number (RN) were developed. IRI can be defined as the cumulative relative displacement of the axle with respect to the frame of reference quarter-car per unit distance travelled over the pavement profile at a speed of 80 km/h. It is expressed in m/km or in/mi at selected intervals (e.g. every 100 m) (Papagiannakis & Masad, 2008). Higher IRI values indicate high roughness levels. RN is the index in the scale of 0 to 5 range, 5 representing a perfect ride, and computed from the profile data of pavement elevation.

2.3.2. Surface distress

Surface distress comprises of a variety of distresses present on pavement surface occurring due to loading, environmental effects, construction defects, or a combination of these. Measurement of distress type, its severity, and density are required during condition evaluation. Such data is typically collected manually, or by using semi-automated/automated tools (TAC, 2013). In the manual survey, observation, and measurement of pavement deterioration is done directly by people. It is either performed by evaluators walking along the pavement or in a moving vehicle, where it is known as windshield surveys. Although this method is more realistic but requires considerable time, and human efforts. In a rather quick, safe, and more reliable method, vehicles or trailers equipped with video cameras, lasers, and other sensors collect instantaneous data while passing on the road. Analysis of collected data using automated or semi-automated software reports the distresses (Tighe et al., 2008). A variety of distresses are found on asphalt pavements and can be grouped under cracking, deterioration, and surface defects. Almost all of them have three severity levels namely low, medium, and high (ASTM D6433-09, 2009).

2.3.3. Safety

The aspect of safety is governed by the parameter surface friction or skid resistance. It is the force which resists sliding of tires on pavement. Friction is the factor concerned with road accidents. Apart from pavement texture, conditions like tire pressure, the tread of a tire, presence of water, and vehicle speed also affect skid resistance. Devices to measure skid resistance, such as friction tester, mu meter, and British pendulum tester based on wheel arrangement type of locked wheel, fixed slip speed, variable slip speed, or side force in yaw mode have been developed. The operating principle for all the devices is same where the coefficient of friction is measured as the ratio of shear force measured between tire, and pavement; and normal reaction.

2.3.4. Structural capacity

Structural capacity is the capacity of pavement to bear the loads imparted over it during its lifetime. Surface deflection is considered to be the characteristic of the pavement's structural capacity. The devices used to measure in-situ pavement surface deflection are referred as deflectometers, and explained later in this chapter, in detail. Additionally, they also provide information about the engineering properties of pavement layers and subgrade. Therefore, measuring deflection data is of primary concern to the engineers. In addition to surface deflections, bond conditions at the layer interfaces greatly impacts the structural integrity of pavements. The following section discusses the phenomenon of loss of this bond, in detail.

2.3.4.1. Delamination between HMA layers

Delamination between HMA layers of asphalt pavements primarily occur due to improper tack between the paved layers or overlay, and existing pavement surface. In order to ensure this adhesion, an appropriate amount of tack coat is applied at the interface. Tack coat is defined as an application of asphalt material to an existing relatively non-absorptive surface to provide a thorough bond between old and new surfacing (ASTM D8-02, 2002). Generally, liquid asphalt, asphalt emulsion, cut–back asphalt or polymer-modified asphalt are used as tack coat materials. Asphalt emulsions are preferred due to their inherent advantages of being free from harmful volatile solvents and capable to be applied at lower temperatures. The temperature of tack coat material highly affects its viscosity. Low viscosity material provides better interlocking as it can easily penetrate and fill the surface irregularities.

A number of studies are available that report on the effect of factors contributing to the loss of bond in asphalt layers, during construction and operation. During construction stages, the rate of application of tack coat (poor, excessive or non-uniform), poor quality control, laying in cold weather, infiltration of water, faulty construction equipment or machinery, poor compaction of underlying layers and subgrade; negatively affect the bond strength between the layers (Lepert et al., 1992). During operational phases, environmental effects, repeated loading and unloading cycles in the vertical direction, and turning, braking or acceleration/deceleration of vehicles, horizontally displace the layers by the development of shear stresses at the interfaces (Wellner & Hristov, 2015). In the majority of the cases, this occurs either at high loading, or high temperature, or combination of the two conditions (Celaya et al., 2009). Research findings consistently emphasize on the fact that interlayer bond strength decreases significantly with increasing temperature (Bae et al., 2010). This is due to the fact that viscosity of tack coat asphalt reduces with increase in temperature, ambient as well as test temperature. The shear bond strength in such cases solely depends on aggregate interlock and friction between the layers. Presence of water at the interface further accelerates the propagation of delamination due to development of hydrostatic pressures imposed by traffic. Researchers have found that a 10% decrease in bond strength can cause as much as 50% reduction in fatigue life of pavements, and reduce overall life by 10-12 years (West et al., 2005). Studies report many mishaps due to the same (Chen, 2010; FAA, 2014a; Tsubokawa et al., 2007).

2.4. Methods to identify delamination between HMA layers

Being a subsurface pavement deficiency, delamination is difficult to be detected at early stages. Upon reaching high severity levels, it appears visually over the pavement surface, but meanwhile, it would have adversely affected the structural integrity of pavement to a greater extent. Rectification at this stage due to its increased coverage becomes challenging. Hence, it is highly desirable to get information about its occurrence during the initial stages, for which various testing methodologies have been developed.

2.4.1. Destructive testing methods

Destructive testing can be performed either by employing the coring/cutting based in-situ methods or by laboratory testing of field core samples. Numerous studies have been conducted on destructive/semi-destructive testing for debonding evaluation. Different countries have developed their own test methods and patented devices. However, literature reports that there is still a need for an internationally acceptable standard test method (Rahman et al., 2016). Different modes of pavement interface failure have been identified from the literature and it may be classified as shear, tensile, shear-compression, and shear-tensile (Sutanto, 2009; Tseng & Jameson, 2019). Based on these modes of failures, the testing methods can be grouped as shear and tensile test methods. Direct shear test performed with or without normal load, is the most common test under shear test method category, frequently performed using Leutner test device. Layer-parallel direct shear and Florida department of transportation shearing test device are devices similar to Leutner device (Partl et al., 2018). Torsion bond test is another type of shear test in which torque is applied to the surface of pavement until it fails. Manual torque bond test, and automatic torque bond test are few such test devices. Tensile test methods include pull-off tests that evaluate the direct tensile strength of the pavement interfaces. Indirect tensile testing is performed using a wedge splitting test in which a wedge is introduced at the interface until the layers separate. Three-point and four-point shearing tests are a few other methods for interface bonding evaluation (Rahman et al., 2016).

2.4.2. Non-destructive testing methods

It is desirable that the testing method neither damages existing pavement structure, nor interrupts traffic operations. Also, it should preferably be quick, reliable, and consistent in obtaining data. Non-destructive testing methods offer these features and provide an ideal testing alternative. Numerous established NDT technologies are available for the evaluation of pavements and can be broadly classified on the basis of deflection-basin or wave propagation approaches (Goel & Das, 2008). The present study focusses on the detection of delamination in asphalt pavements using NDT methods, and in this context, various NDT methods are discussed briefly along with their theory and applications.

2.4.2.1. Deflection-basin methods

Deflection-basin methods consist of applying a load and measuring deflections vertically at different points of the pavement surface. The applied load can be static, oscillatory or impulse type in nature. The deflection data can be directly correlated to the performance of the pavement or used to evaluate its strength, overlay thickness estimation, debonding assessment, estimation of elastic moduli of pavement layers, etc. These parameters further relate to remaining life estimation of in-service pavements, and their evaluation for rehabilitation alternatives. Devices such as Falling Weight Deflectometer (FWD), Heavy Weight Deflectometer (HWD), and Light Weight Deflectometer (LWD) work on this principle.

2.4.2.2. Wave propagation methods

These methods are based on propagation of waves and employ generation/transmission/ propagation of elastic/stress or electromagnetic (EM) waves in the multi−layered pavement structure. A localized impact, such as an impact from a hammer or a piezoelectric or ultrasonic transducer, results in the generation of waves, comprising of both Body Waves (BW), and Surface Waves (SW) (Goel & Das, 2008). The response of the waves, in the form of vibration of the media surface, is captured, and signals are processed to extract subsurface information, such as thickness and moduli of layers, location of interfaces, interlayer bond condition, detection of internal flaws/cracks, etc. (Goel, 2011). Devices working on this principle include Impulse Response (IR), Impact Echo (IE), and Spectral Analysis of Surface Waves (SASW). In the methods relying on EM waves, the change in properties of layers or material, if any, cause the reflections of the transmitted waves. These signals are recorded and analyzed to deduce the required information. The equipment working on this approach include Ground-Penetrating Radar (GPR) and infrared thermography.

2.5. NDT methods for delamination detection between HMA layers: theory and practice

2.5.1. Falling weight deflectometer and other deflection-basin methods

Falling weight deflectometer, as mentioned earlier, is a deflection-basin method to indicate the structural condition of pavement layers. It works on the principle of application of transient impulse type load on the pavement surface to measure the deflection response of layers. A typical FWD used to evaluate highways in India uses a 0.3 or 0.45 m diameter circular loading plate, 50-350 kg of falling mass, 0.1-0.6 m height of fall and six to nine velocity transducers (geophones) (IRC 115, 2014). Heavy weight deflectometer is another variant which is widely used for airport pavements where heavier loads (30-240 kN) are applied to simulate aircraft loading (Turner et al., 2003).

The data processing involves the process of back-calculation that starts with assumed elastic moduli values to obtain calculated deflection values. These calculated values are then compared with observed deflection values. If the calculated and observed deflection values do not match, the assumed moduli values are further adjusted and the iteration continues until they match closely. Several computer programs have been developed for back-calculation that employ a forward model and specific back-calculation procedure (Kang, 1998). Light weight deflectometer is a similar light weight version of FWD. Its back-calculation can be performed using commercial software LWDmod, which calculates the in-situ modulus using Eq. (2.1).

$$E(MPa) = \frac{A * P * r * (1 - \nu^2)}{d} \tag{2.1}$$

where, E = in-situ modulus (MPa), A = plate rigidity factor, 2 for a flexible plate, and π/2 for a rigid plate, P = maximum contact pressure (kPa), r = plate radius (m), ν = Poisson's ratio (usually in the range 0.3 to 0.45 depending on test material type), d = peak deflection (mm). Rolling Dynamic Deflectometer (RDD) is an offshoot of FWD which provides continuous deflection measurements so that the vehicle needs not to be stopped for testing. It can rapidly identify areas requiring rehabilitation and is found to be valuable for airfield pavements (Bay et al., 2000).

Earlier studies report equipment such as deflectograph and curviameter to check their suitability for pavement debonding measurements but were not found suitable to detect debonding, and as such the available related literature is scarce (Lepert et al., 1992). Although LWD was found to show varying deflection profiles at various sections of asphalt pavements, yet the reason for this variability could not be ascertained (Heitzman et al., 2013). Recent researchers have achieved some success in using FWD for debonding assessment. Celaya et al. (2009) concluded FWD to be more accurate for wide fully debonded areas, located at shallow depths than the ones with deep debonding. It is expected that debonded areas would undergo higher surface deflections than the bonded or intact ones. Gomba (2004) reported lower values of forward calculated surface layer moduli as an indication of the presence of debonding. Comparison of maximum deflections given by each geophone with various deflection basin parameters did not provide any significant difference for intact, and debonded sections. However, the difference in FWD time histories was seen in the unloading portion where deflections of debonded sections were quicker and higher recovered (Heitzman et al., 2013). Simonin et al. (2015a) found that the slope of the deflection bowl was a more sensitive parameter to debonding, in case of semi-rigid pavements. In the case of

HWD, central deflection values were significantly affected by interlayer quality rather than the outer ones and were verified using numerical simulations (Amir et al., 2016).

2.5.2. Impulse response

Impulse response technique is based on analyzing the dynamic response of pavement structure due to an applied impulse (ASTM C1740-16, 2016). It consists of a hammer instrumented with a load cell (piezoelectric) to create a low-strain impulse, and a closely placed transducer (geophone), to detect the system response, in the time domain (Kruntcheva et al., 2004). The impact generated is much stronger, and the range of frequency used in testing is 0 to 1 kHz (Gucunski et al., 2013). Different analysis approaches have been tried by the researchers, one among them involves modelling the pavement as a single degree of freedom system (Gucunski et al., 2013; Taylor, 2013).

IR method provides reliable qualitative information about interface bond through visual inspection of its signals. Debonded or partially bonded surfaces of asphalt pavements produced enhanced dynamic response to the provided impulse (Kruntcheva et al., 2004; Sangiorgi et al., 2003). Approach to quantify bond condition used the auto-power spectrum of the accelerometer response to define an area ratio (Sangiorgi et al., 2002). In another approach by Kruntcheva et al. (2004), the magnitude of input-output transfer function estimate were used whereas the theory of fractals, and fractal dimension measured from acceleration time history was utilized by Sangiorgi et al. (2003). The IR method has been found to be comparatively more successful for detecting fully and widely debonded areas, located at shallow depths (Munoz, 2009). For thin surfaces (10–50 mm), it was found to provide reliable results in detecting localized debonding over 300 mm radius area but numerical simulations have shown that it can detect delamination defects of size greater than 300 mm located up to 100 mm depth (Munoz, 2009). However, in recent studies, it was found to poorly perform in identifying delamination between asphalt layers (Heitzman et al., 2013).

2.5.3. Impact echo

Impact echo method is based on the principle that a significant reflection of stress waves (P-waves) occur whenever they encounter a substantial change in stiffness of medium or large contrast in the acoustic impedance. The resonant or return frequency of reflected P-wave from delamination or interface is captured to identify the severity of defect (ASTM C1383-15, 2015). The test method consists of generating low-frequency P-waves up to 20−30 kHz using a mechanical impact source (steel balls of different sizes may be used as an impact source). Surface displacement caused by direct and reflected waves through internal flaws or interfaces (difference in acoustic impedance) is detected and recorded in time domain using a transducer (geophone), mounted on the surface near the impact location (Carino, 2015). The pattern of waveform provides information about the internal defects, and some specific signal processing techniques such as Blackman-Harris temporal window have been recommended to facilitate interpretation of signals (Medina & Garrido, 2007).

IE method could identify debonding conditions located at a depth of 125 mm in asphalt layers. However, shallow delaminations (50 mm deep) could not be detected, possibly since the required high frequencies could not be excited due to the incapability of the system (Heitzman et al., 2013). Studies have found that the shapes of spectra obtained for bonded, and debonded areas were very different, and amplitude for debonded areas was distributed over wider frequency ranges, however, peak frequencies were found to be similar in both spectra (Celaya & Nazarian, 2007). Authors (Heitzman et al., 2013) reported the detection of approximately 74% of the delaminated areas using IE. Numerical simulations concluded and verified that IE can detect fully, and partially debonded defects even for depths greater than 100 mm (Munoz, 2009). Ultrasonic Pulse Echo (UPE) is a variant of IE which relies on detection of objects, and anomalies using ultrasonic stress waves. These waves are generated by excitation of piezoelectric material with high voltage and current pulse. Application of UPE method shows very good sensitivity to debonded areas, as seen through B-scans (Simonin et al., 2015b; Simonin & Villain, 2016).

2.5.4. Spectral analysis of surface waves

Spectral analysis of surface waves method employs the dispersive characteristics of surface waves (Rayleigh wave) in a multi-layered medium (ASTM D6758-02, 2002). It comprises of an instrumented hammer in the form of SW source to generate waves of desired frequencies, and two receivers (accelerometers) that are placed at known offsets. The method determines shear wave velocity which is a distinctive engineering property of a material (Richart et al., 1970). Data processing involves a three-step procedure which comprises of (i) generating experimental dispersion curve from field testing, which is the plot of shear wave velocity, and corresponding wavelength (ii) theoretical forward modelling of Rayleigh wave dispersion in multi-layered media, by methods such as stiffness-matrix method, and linearized stiffness matrix method (Kausel & Roësset, 1981); finally (iii) inversion/back-calculation in an iterative process to get moduli of all the layers, and generates the vertical stiffness profile of the pavement section (Goel & Das, 2008).

SASW was introduced to determine the in-situ elastic modulus of pavements and has been found to be quiet successful in indicating both shallow (50 mm), and deep debonding (125 mm) (Heitzman et al., 2013; Olson, 2015; Tinkey et al., 2013). Researchers (Tinkey et al., 2013) found a significant decrease in surface wave velocity of the order of 10-20% in the dispersion curve at debonded areas. Others reported damping of signal due to the presence of bonding material at the interface between the two layers. Additionally, amplitude and pattern of the magnitude of auto power spectrum was also found to differ for bonded, and debonded areas (Goel, 2011). A method to quantify interface bond condition between asphalt layers on the basis of shape parameters was proposed (Goel, 2011). The technique is superior due to the fact that approximate depth of debonding occurrence can be obtained from dispersion curves, and moduli data of pavement materials at debonded as well as sound locations can be estimated. Ultrasonic Surface Waves (USW) method is a variant of SASW that consists of generating ultrasonic frequencies and hence low wavelengths, thus resulting in the shear wave velocity profile staying within the uppermost layer. It has been found to detect fully debonded areas located within 100 mm depth (Munoz, 2009). Nazarian et al. (1993) developed automated testing equipment called seismic pavement analyzer and later implemented it into a portable hand−held device called the Portable Seismic Property Analyzer (PSPA) which can automatically, and simultaneously conduct both IE and USW tests. It has reported to detect about 69−78% delamination defects successfully (Heitzman et al., 2013). Multichannel Analysis of Surface Waves (MASW) is another variant, in which other higher modes of surface waves are detected using an array of receivers (Park et al., 1998).

2.5.5. Ground-penetrating radar

Ground-penetrating radar is a real-time NDT method that is based on the principle of transmitting electromagnetic pulses into the probed material and detecting the reflected pulses as they confront any discontinuity with different dielectrics. The manner in which the radar energy will respond to any material would depend on electrical conductivity and dielectric constant of the material. For low conductivity materials, the attenuation losses are less and radar energy penetrates deeper. A higher dielectric contrast, or difference in dielectric between the two materials, results in a stronger reflection in the radar signal. GPR system consists of a pulse generator to generate known short pulses (~10^{-9} s) of EM wave, and an antenna to transmit the pulse into the subsurface system (Benedetto et al., 2017). As the pulse travels into the subsurface system when it encounters the interface of next layer or any material with different electrical properties (dielectric constant), a part of its energy gets reflected back and remaining gets transmitted to the next layer. A receiver captures the reflected signals and records their amplitude and arrival time (Saarenketo & Scullion, 1994). The reflected energy form a series of pulses termed as radar waveform which contains information regarding material properties and thickness of layers (Maser & Scullion, 1992). The dielectric constant of the first layer of layered pavement can be estimated as given by Eq. (2.2).

$$\varepsilon_{r,1} = \left(\frac{1 + \left(\frac{A_0}{A_P}\right)}{1 - \left(\frac{A_0}{A_P}\right)} \right)^2 \tag{2.2}$$

where, $\varepsilon_{r,1}$ is the dielectric constant of the first layer, A_0 is the amplitude of surface reflection and A_P is the amplitude of incident GPR wave.

Asphalt layers containing debonding of different thicknesses showed the increased amplitude of reflection signals (Dong et al., 2016). The authors (Dong et al., 2016) proposed a delamination factor for detecting delaminated areas of asphalt pavements. A recent work concludes that the debonding is also indicated by decrease in amplitude of frequency spectrum (Rodes et al., 2020). Field tests confirmed that GPR could detect the presence of moisture and stripping condition at 100 mm depth in asphalt pavements but failed to detect extensive areas of debonding in absence of moisture (Heitzman et al., 2013). Numerical simulations, and applications of new algorithms proved GPR to be successful in determining debonding with water-filled delaminations clearer than the air-filled delaminations of the same size (Heitzman et al., 2013; Smith & Scuillion, 1993). Todkar et al. (2017) reported the use of supervised machine learning algorithm to detect the presence debonding within asphalt pavements. Recently, advanced signal analysis using amplitude ratio test and support vector machines was employed to detect thin artificial debondings (Todkar et al., 2019). GPR has been highly successful for locating underground anomalies. GPR studies show that detection of subsurface anomalies up to 0.6 m with a 1 GHz horn antenna, and up to 0.4

m with a 2 GHz horn antenna is possible in asphalt pavements (Heitzman et al., 2013). It is also possible to approximately estimate the depth of defect, and anomaly.

2.5.6. Infrared thermography

Infrared thermography is based on capturing the thermal signature of the surface of a material, to locate the areas that have some anomaly or inhomogeneity. This is possible due to the fact that subsurface anomalies present in any material hinder the heat flow through that material, and create localized surface temperature variations (Malhotra & Carino, 2004). Bodies at temperatures over 0 K emit radiations in the infrared wavelength of the spectrum, proportional to their temperatures (Solla et al., 2014). The emitted infrared radiations are detected by infrared measuring devices using Stefan–Boltzmann's law, which is expressed as shown in Eq. (2.3).

$$\frac{q}{A} = \varepsilon \sigma T^{4} \tag{2.3}$$

where, q is the rate of energy emission (W), A is the area of the emitting surface (m^2), T is the absolute temperature (K), σ is the Stefan–Boltzmann's constant ($\sigma = 5.676\times10^{-8}$ $Wm^{-2}K^{-4}$) and ε is the emissivity of the emitting surface for a fixed wavelength and absolute temperature T. Emissivity is unity for a perfect blackbody, but it is always less than unity, for real surfaces.

Infrared measuring devices transform the acquired radiations into electronic signals (Wolfe & Zissis, 1978). Further, a colour is assigned to each infrared energy level to convert the acquired images into visible images. A warmer object is indicated by the spectrum of red or orange colour while blue or violet colour indicates cooler object (Schmitt et al., 2015). The method is based on two approaches: passive and active. The passive approach makes use of thermal radiations emitted by the surface of the test body under natural conditions. In the active approach, thermal excitation is applied by an external energy source to produce a thermal contrast between the areas of study, and the surrounding ones, either by heating or cooling the object (Milovanović & Pečur, 2016). Presence of subsurface anomalies, voids, cracks or delaminations in any material interrupt the heat flow through them, warm faster than surrounding areas and appear in thermal images as hot spots, during the day time. At night, they dissipate heat faster than the surrounding, and appear in thermal images as cold areas (Ahlborn & Brooks, 2015; Heitzman et al., 2013; Weil, 1996).

Infrared thermography field investigations performed on asphalt pavement showed its potential to identify the delamination, stripping, voids and other anomalies located at shallow depths (40-70 mm), (Heitzman et al., 2013; Tsubokawa et al., 2007). Various external factors, such as intensity and amount of solar radiation, the maximum and minimum temperature in a day, ambient air temperature variation between day and night, wind and humidity affect the defect detection (Golrokh & Lu, 2019; Moropoulou et al., 2000; Tsubokawa et al., 2007). Numerical simulations have shown that air-filled delaminations can be detected by a typical commercial infrared camera, whereas those containing moisture are difficult to be detected (Heitzman et al., 2013). The method suffers from the inherent limitation that it could not determine the depth and dimensions of the defects, and suitable for shallow debonding only (Moropoulou et al., 2002; Solla et al., 2014). The primary characteristics along with advantages and limitation of NDT technologies based on the two approaches are presented in Tables 2.1 and 2.2.

Table 2.1. Performance summary of deflection-basin methods for delamination detection in asphalt pavements

NDT method	Load type	Magnitude	Frequency	Remarks
FWD	Impact	25-80 kN	30−32 Hz	• Accuracy of 30-65% achieved • Provides point measurements • Better detection of fully debonded areas located at shallow depths • Impulse duration too long to focus on top thin layers • Detection of presence of internal defects in concrete pavements is difficult
HWD	Impact	30−240 kN	30−32 Hz	• Provides point measurements • Qualitative information • Suitable for large size defects • Mostly used in airfield pavements
RDD	Dynamic	4.45−310 kN	5−100 Hz	• Provides continuous deflection profiles • Can be used to identify locations where discrete testing should be performed • Capable of quickly identifying changing pavement responses • Measurement speed is up to 2.4 km/h

Table 2.2. Performance summary of wave propagation methods for delamination detection in asphalt pavements

NDT method	Wave/ Frequency range	Depth achievable	Accuracy	Remarks
GPR	EM/0.3− 3.0GHz	up to 5.0 in.	25−70%	• Capable to test full lane width • Poor detection of debonding in the absence of moisture • Higher frequency antenna (3.0 GHz) could detect air-filled debonding • Measurement speed up to 18 m/s
IR	BW/0−1kHz	up to 5.0 in.	45%−100%	• Reliable for the detection of the shallow and deep fully debonded areas • Rapidly locate weak spots in pavement • Depth to rigid layer and presence of water table affect results • Require site specific temperature adjustments
SASW	SW/<20kHz	up to 7.0 in.	35−85%	• Able to detect depth of delamination location more accurately • Capable to detect both shallow and deep debonding • Measurement speed up to 2 m/s
USW	SW/>20kHz	up to 5.0 in.	59−78%	• Reasonable accuracy in detecting debonding • Better accuracy obtained for cooler pavement temperatures
IE	BW/up to 50kHz	4.0−12.0 in.	74%	• For effective results, significant contrast between modulus of adjacent layers is required • Very small debonded areas do not affect response • Difficult to observe shallow delaminations at depth less than 2 in. • Colder temperature testing enables proper detection since asphalt require sufficient stiffness to generate detectable reverberations • Measurement speed up to 2 m/s
IRT	Infrared	1.5−3.0 in.	±2 °C	• Suitable for very shallow and severe delamination • Dependent on environmental conditions • Active methods provide better results • Unable to determine exact dimensions of defect • Unlike GPR, presence of moisture in debonded areas reduces chance of their detectability

2.6. Bridge management systems

Akin to pavement management systems, Bridge Management System (BMS) has been devised to facilitate the ease for optimizing serviceability and safety of bridges within budgetary constraints. A typical BMS comprises of inventory, condition evaluation, deterioration prediction, life-cycle cost estimation, and maintenance and optimization, which are very much similar in functionality to the components of PMS. Whether the requirement is for prediction of future performance, estimation of agency and user costs, or optimization of M&R needs, the vital component to serve well all these activities is a reliable assessment of current bridge condition.

The conventional and easy assessment methodology involves conducting visual surveys that primarily produce subjective and qualitative outcomes by relying on expertise and knowledge of bridge inspectors. With the advancement in technology, a significant focus is shifted on NDT technologies due to their noteworthy advantages of being quick, reliable, and objective. In addition to NDT, continuous monitoring using in-situ embedded sensors known as structural health monitoring is highly effective to capture response associated with the material, load, and environmental effects (Alampalli, 2012). Its fundamental elements are sensors and instrumentation, structural evaluation, and assessment to support M&R decision-making (Feng & Feng, 2018; Wong, 2007). However, it is not feasible and economical to install embedded sensors on a wider scale. Moreover, load testing response and simulations on the reliability of bridges using finite element platforms are also gaining importance (Omar & Nehdi, 2018).

NDT offers the ability to monitor the aging infrastructure of bridges in an effective manner. Its outcomes would also complement to predict life-cycle costs of bridge infrastructure. Bridge owners and engineers can continuously assess the deterioration as well as the efficiency of Maintenance, Rehabilitation and Replacement (MR&R) alternatives at various stages. It would aid to prevent a premature, and sudden collapse of bridge decks. This section discusses the common bridge deck deterioration phenomenon, and success achieved using NDT in bridge condition assessment studies.

2.6.1. Condition assessment of concrete bridge decks

Safety issues of bridges are among the highest causes of concerns to the highway agencies. The cost of MR&R of bridges is also very high. Therefore, efficient and reliable condition assessment of bridge decks is crucial to assist the agencies so as to timely take appropriate MR&R needs. The condition evaluation of an existing bridge aims to investigate if the bridge would remain safe and functional over its residual service life. The loss of integrity occurs due to the action of traffic loading as well as environmental factors. Various deterioration mechanisms include corrosion, alkali-silica reaction, fatigue, shrinkage, carbonation, and overloading. However, the most common deterioration phenomena with great concern to engineers can be classified as corrosion, delamination, vertical cracking, and concrete degradation (Gucunski et al., 2013).

2.6.1.1. Corrosion

Corrosion in reinforcement steel adversely affects the structural integrity of the deck to a great extent. By causing the development of internal stresses, corrosion also leads to cracks, delaminations or surface fractures. Application of deicing salts on roads is a major contributor to this problem by causing chloride diffusion. The natural protection of reinforcement steel against corrosion by the formation of oxide film provided by highly alkaline cement-based material and concrete gets destroyed by chloride diffusion. Once it is destroyed, the corrosion process begins, and its rate depends on factors, such as temperature, humidity, and pH of water. Alternate wet and dry cycles, accelerate the process of corrosion. Apart from chloride-induced blackish colour corrosion, there also occurs carbonation-based, red or brownish colour corrosion.

2.6.1.2. Deck delamination

Corrosion of embedded steel reinforcement causes an increment in volume of rebar, and initiate crack which further progresses to fracture planes along the level of reinforcement. The detection of this internal defect is difficult since it is not visible on the concrete surface, and may ultimately lead to open spalls. Hence, it requires immediate attention before the structural capacity of deck reduces.

2.6.1.3. Vertical cracking

Many additional phenomena other than corrosion, such as traffic load, freeze-thaw cycles, plastic shrinkage, ambient temperatures, and hydration heat induce cracking in bridge decks. Such cracks mostly occur vertically in contrast to corrosion-induced horizontal cracks.

2.6.1.4. Concrete deterioration

Concrete deterioration can be considered by a reduction in its modulus or strength value, due to the action of phenomenon such as cracking, freeze-thaw cycles, plastic shrinkage, and alkali-silica reaction. In alkali-silica reaction, silica gel is produced which gets swollen in the presence of water and induce deformation along with a network of cracks. Cracks also generate along deck slabs due to plastic shrinkage causing volume reduction. Hydraulic pressure in concrete gets further increased during freeze-thaw cycles, and once it exceeds the tensile strength of concrete, concrete ruptures. Excessive exposure to freeze-thaw cycles eventually causes scaling, cracking or crumbling.

2.6.2. NDT methods for delamination detection in bridge decks

The basic form of bridge condition evaluation is visual inspection. Despite the fact that it is subjective and qualitative, it has been a prevalent practice. Its advantage is a thorough evaluation of the entire infrastructure without being limited to the detection of any specific defect. However, it has been established from the research that visual inspection as a standalone method is unreliable (Moore et al., 2001). This has motivated the development of advanced assessment procedures. Application of simple and affordable NDT tools such as hammer sounding and chain dragging has been a predominant practice on concrete bridge decks. These test methods do not provide quantitative data, and their interpretation relies on the inspector's experience and judgment. A recent study makes an attempt to determine delamination by converting the captured sound into spectrogram and classifying it using convolutional neural network following inception v3 model (Sarmiento et al., 2019). Although they have their own merits, these techniques are also unreliable due to inherent subjectivity (Yehia et al., 2007). In recent works, as a modification to chain dragging, ball-chains have been used to create continuous impact excitation, integrated with air-coupled sensing to rapidly scan bridge decks (Sun et al., 2018). However, these methods work effectively on shallow delaminations only.

Superior NDT technologies, such as electrochemical method based devices including Half-Cell Potential (HCP), Electrical Resistivity (ER), and Galvanometric Pulse Measurement (GPM) for corrosion, while impact echo, pulse-echo, ground-penetrating radar, and infrared thermography for delamination, and ultrasonic surface waves for vertical crack estimation, can be employed. Section 2.5 has discussed the basic principles of a few NDT devices. Further details of electrochemical methods, their instrumentation, data analysis, and applications are available in various sources such as SHRP (Gucunski et al., 2013), AASHTO Manual for Bridge Evaluation, (AASHTO, 2018) and ACI report.

Impact echo with its development in the 1990s became a popular method for concrete delamination detection (Sansalone & Streett, 1997). In bridge decks, the technique could detect zones of various stages of delamination, from initial to progressed and developed stages (Gucunski et al., 2000). Accuracy of the delamination detection in bridge decks of more than 80% was reported (Azari et al., 2012). However, very small delaminated areas in concrete structures with concrete overlays and concrete slabs with asphalt concrete overlays were found insignificant to its response which became apparent with the increase in delaminated area (Lin & Sansalone, 1996). Mild or colder temperatures are recommended to be optimum for IE testing on bridge decks with asphalt overlays since asphalt is stiffer at colder temperatures, hence short duration, high energy signals could be easily obtained (Sansalone, 1993). A recent study concludes temperature range of zero degree Celsius or below to be appropriate to detect defects in the underlying deck (Azari & Lin, 2019). The conventional IE technique is time-consuming for testing large structures, and need a sensor, and surface contact. To ease this task, air-coupled IE was developed that replaced the contact sensor by a microphone (Zhu, 2008). Another innovation in air-coupled sensing was the use of micro-electro-mechanical sensor by Ham & Popovics (2015). In spite of this development, source of impact remained a limitation for quick data collection process. Development of automated impact sources such as excitation using liquid or ice, and few other techniques faced issues such as weak pulse amplitude, or complex design (Mazzeo et al., 2014). Success has been attained using UPE method that measures the travel time of ultrasonic waves propagating through structure, and being reflected to the surface to indirectly detect defects in concrete (Gucunski et al., 2013).

Ultrasonic surface waves were primarily used to estimate modulus of material along with deterioration in bridge decks, such as the location of vertical cracks, and delaminations (Gucunski et al., 2013). Li et al. (2016) utilized USW in PSPA and found that the average elastic modulus of the deck in deteriorated areas is much lower than in intact areas, due to reduction in the velocity of the surface wave while propagating into internal defects. The investigation of bridge decks using impulse response method to detect shallow delaminations concluded with several limitations of the method (Clem et al., 2013).

Ground-penetrating radar has been extensively used to determine layer thicknesses, air voids, in-situ density estimation, corrosion, and delamination in bridge decks (ASTM D4748−10, 2015; Dong et al., 2016; Leng & Al−Qadi, 2014; Maser, 1996). Most studies use the amplitude of reflection from the reinforcement layer to evaluate the deck condition (Martino et al., 2016; Hong et al. 2017). As per ASTM D6087-08 (2015), deterioration is indicated by 6-8 dB drop in amplitude relative to maximum amplitude. However, it may not apply to severe or no deterioration. In a study conducted by Maser (1996), it was reported that 1−2 mm wide delaminations were difficult to resolve using GPR since even at 1 GHz, its wavelength in concrete (~100 mm) is too large. Therefore, the onset of delamination could not be detected. In another work by Rhazi et al. (2003), GPR failed to detect delamination clearly, and unambiguously in concrete bridge decks with asphalt coating, possibly due to low dimension of delamination, its proximity to reinforcement, and insufficient resolution to the radar antenna. However, laboratory tests on concrete slab could detect delamination as small as 1 mm using stepped-frequency radar (Huston et al., 2000).

Thermal imagery using infrared thermography has shown promising results in detecting subsurface delaminations of concrete bridges (ASTM D4788-03, 2013; Omar et al., 2018; Washer & Fuchs, 2015). Accuracy of 60-70% in delamination detection has been reported using IRT (Ahlborn & Brooks, 2015). However, success is asserted to be dependent on various attributes in case of passive thermography. Appropriate weather conditions and collection of data at the right time of day and night cycle is found to largely govern the detection of flaws in passive thermography (Kee et al., 2012). Different authors have made different recommendations regarding the time of data collection when the defect is detectable such as 5-9 hours after sunrise, 40 minutes after sunrise, and night cooling cycle (Gucunski et al., 2013; Hiasa, 2018; Kee et al., 2012; Washer et al., 2010). Area of delamination was found to be a key factor of detectability rather than its thickness or volume, and authors Vaghefi et al. (2011) made an attempt to calculate the percentage of the delaminated area using thermal infrared images. Use of three-dimensional optical bridge evaluation system and ArcGIS along with thermal infrared imagery was suggested in another study, to identify and quantify the bridge deck data (Vaghefi et al., 2015). Sultan & Washer (2016) put efforts to develop a quantitative analysis method for the reliability of delamination detection based on the pixel-by-pixel comparison. To detect the presence of delamination, the authors reported optimum threshold value for the thermal contrast to be 0.8 °C and 0.6 °C for fabricated and in-service bridge decks, respectively. While Washer et al. (2010) have concluded that in absence of solar loading, a positive or negative ambient temperature change of at least 8.3°C (15°F) could be used as a standard practice to assess subsurface defects. In order to make IRT more practical and faster inspection method, Hiasa (2018) implemented bridge testing using IRT at highway driving speeds. Ahlborn & Brooks (2015) used both the active and passive approaches of IRT along with 3D photogrammetry detecting cracks, spalls, and delaminations at near highway speed. Maser (2004) has recommended the use of active infrared thermography by employing high-intensity pavement heaters to briefly heat the entire concrete bridge deck. The cost and time of testing are reported to get highly reduced as compared to chain drag testing operations. However, the technique has not found capable to detect corrosion or cracks and does not provide the depth of flaws (White et al., 2015). In spite of success obtained for delamination detection, studies have reported that deeper delaminations have less chances to be detected, particularly the ones deeper than 51 mm (Gucunski et al., 2013; Kee et al., 2012; Yehia et al., 2007). As stated earlier for asphalt pavements, IRT is not able to estimate the depth and dimensions of defect, and it remains a limitation of this method.

Literature studies reveal that no single NDT is capable to provide a full picture of structural condition which encouraged the researchers to use multiple technologies for the evaluation (Gucunski et al., 2000, 2013; Kee et al., 2012; Oh et al., 2012; Omar & Nehdi, 2016; Yehia et al., 2007). Moropoulou et al. (2000) suggested that a combination of IRT with GPR may provide reasonable results. Gucunski et al. (2013) conducted an extensive evaluation of fabricated, and in-service bridges for delamination, cracks, and corrosion detection using a variety of NDT tools. White et al. (2015) used a combination of IRT, GPR, and ultrasonic tomography on bridge deck condition assessment, and argued that the multi-method NDT approach is more robust than the methods used individually. Sun et al. (2018) demonstrated that combining acoustic scanning, and GPR would provide a comprehensive evaluation of concrete bridge decks.

Table 2.3 summarizes the performance of various NDT technologies for evaluation of different deterioration mechanisms in bridge decks.

Table 2.3. Performance summary of NDT technologies for bridge deck evaluation

NDT	Deterioration type	Accuracy	Speed	Ease	Precision
IE	Delamination	High	Slow	Medium	High
Chain drag	Delamination	Medium	Moderate	Easy	Medium
IRT	Delamination	Medium	Very fast	Easy	Low
GPR	Delamination	Medium	Fast	Moderate	High
	Corrosion	Low	Fast	Moderate	High
USW	Delamination	High	Slow	Tough	Medium
	Crack	Medium	Slow	Tough	High
	Concrete degradation	High	Moderate	Tough	High
HCP	Corrosion	High	Fast	Easy	Medium
GPM	Corrosion	Medium	Moderate	Moderate	Medium
ER	Corrosion	High	Fast	Easy	High

Source: Compiled from Gucunski et al. (2013).

2.7. Pavement prioritization techniques

By virtue of budget limitations, it becomes difficult to attend the M&R necessities of all pavement sections within the stipulated time and hence need arises for priority ranking of pavement sections. Prioritization of pavement sections is a systematic process that helps to economically allocate an annual budget for executing M&R or rehabilitation activities. It becomes an effective decision-making tool for efficient PMS. Conventional method employed the ranking to be allotted based on the judgment provided by field experts, engineers, and maintenance personnel. The literature on pavement condition assessment and prioritization reveals widespread applications the fuzzy set theory due to its objectivity, and tolerance for incorrect data. This section discusses the various approaches with special focus on fuzzy-based techniques.

For assigning priority ranking to pavement sections, formulation of numerical indices known as condition indices is practiced. It involves summarizing the distress data into a performance indicator. Literature reports broadly two methodologies to develop an index; using master curves or subjective judgment by experts. The approach that uses master curves, defines pavement condition based on distress type, its severity, and density, whereas evaluation by experts is based on the results of field surveys transformed using statistical tools. One of the method using master curves, developed by U.S. Army Corp of Engineers, and later adopted as an ASTM standard has gained widespread popularity known as Pavement Condition Index (PCI). It is a numerical value ranging from 0 (failed pavement) to 100 (sound pavement) and determined from the visual survey results. Distress type, their severity, and density govern the degree of pavement deterioration. Therefore, deduct values were developed to estimate the impact of a combination of these three factors on pavement condition. Use of maximum deduct value determines the condition of pavement under study (ASTM D6433-09, 2009). Other indices developed by evaluation from experts include pavement quality index (Haas et al., 1994), distress manifestation index (Chamorro et al., 2009), PSI (AASHTO, 1993), priority index (Reddy & Veeraragavan, 2001), and composite index (Chen et al., 1993). Shah et al. (2013) individually developed separate indices for distress, roughness, structural capacity, and skid resistance, in addition to an overall condition index. These indices consider less number of distress types than PCI and hence require calibration, and modification with reference to their application (Chamorro et al., 2009; Haas et al., 1994). Superior to these is the inclusion of fuzzy logic to develop condition index. Researchers have practiced Fuzzy Weighted Average (FWA) method, neuro-fuzzy approach, Fuzzy Inference System (FIS) of MATLAB, angular fuzzy set model, and multi-objective optimization (Arliansyah et al., 2003; Bianchini & Bandini, 2010; Santos et al., 2020; Wang & Liu, 1997; Wee & Kim, 2006). Fuzzy indices such as overall acceptability index and fuzzy distress index and fuzzy models were developed (Shoukry et al. 1997; Soncim et al., 2019). A few of them have supplemented the indices with computer programs, to ease the task (Prechaverakul & Hadipriono, 1995). Airfield pavement condition index development required parameters such as structural index, PCI, and foreign object damage potential (Greene et al., 2004). Tighe et al. (2004) devised a priority score as a function of PCI, traffic, operational sensitivity, and functional classification to prioritize the airport pavement sections.

For ranking or prioritizing in various decision-making processes, numerous researches have used Multi-Criteria Decision-Making (MCDM) approaches. Analytic Hierarchy Process (AHP) as described by Saaty (1980) has gained popularity since the last decade for prioritization projects due to its intuitive and efficient approach in extracting judgments through pairwise comparisons (Ahmed et al., 2017; Dabous et al., 2020; Dalal et al., 2010). Ramadhan et al. (1999) used AHP for priority ranking of pavement maintenance. Farhan & Fwa (2009) applied absolute AHP, ideal-mode relative AHP, and distributive-mode relative AHP to prioritize pavement maintenance activities and concluded absolute AHP to be suitable for such cases. Khademi & Sheikholeslami (2010) utilized Conference-Delphi-AHP model for low-class road maintenance. Dabous et al., (2020) used AHP and multi-attribute utility theory to rank and prioritize pavement sections under sustainability-related criteria. Although AHP provides simple comparisons, however, it cannot capture redundancies, misjudgments, and partial truth that is inherent in opinion and judgment of decision-makers while assigning weights. These are brilliantly handled by fuzzy logic which is capable to model complex nonlinear functions. Researchers adopted using AHP in combination with fuzzy logic (Babashamsi et al., 2016). A study by Moazami et al. (2011) prioritized pavement alternatives using AHP and fuzzy decision-making with Gaussian membership functions and parameters, such as PCI, road width, hourly traffic, cost of rehabilitation and maintenance. Sun & Gu (2011) applied AHP and fuzzy logic theory using deflection, roughness, surface deterioration, skid resistance, and rutting as five performance indicators using maximum graded principle and defuzzified weighted cumulative index for evaluating highway pavement sections. Chandran et al. (2007) used fuzzy condition indices by formulating fuzzy membership functions for distress extent, severity, and their relative importance to prioritize the pavement sections of low-volume roads in India. Sandra et al. (2007) prioritized different classes of highways using priority index computed from a fuzzy preference relation matrix based on the functional condition of pavements. Singh et al. (2018) used FWA, and Fuzzy Analytic Hierarchy Process (FAHP) method to prioritize rural road pavement stretches taking surface modulus, IRI, rut depth and friction coefficient into consideration. In another study, Sprouse & Bianchini (2020) proposed a methodology based on fuzzy reasoning to quantify pavement repair rate and its overall impact on the community.

Other techniques, such as ANN was employed in pavement prioritization using function performance parameters (Janani et al., 2019). Singh & Sreenivasulu (2005) used the Highway Development and Management (HDM-4) tool for prioritizing the pavement sections on the basis of net present value and benefit-cost ratio. Other studies on the economic viability of M&R projects also utilized HDM 4 software (Chopra et al., 2017; Parida et al., 2011). HDM 4 is a powerful tool for optimizing the budgetary constraints, but large data requirements sometimes act as its limitation particularly in developing countries.

2.8. Pavement condition prediction models

Prediction of pavement deterioration has been studied since the early 1960s during the AASHO road test. The prediction models are mathematical expressions of the expected values that a pavement parameter will take in the analysis period (Hudson et al., 1979). Numerous attempts have been made by researchers in the direction to optimize PMS by analyzing pavement distresses and developing condition prediction models. These models can be broadly categorized into deterministic models, probabilistic models, and other approaches. Deterministic models include parameters that are not random and produce stationary outputs. Probabilistic or stochastic models utilizes random variables to estimate probable outcomes. Authors have utilized both the modeling approaches (Huang, 2004). Three offshoots of deterministic models: mechanistic modeling, empirical modeling, and mechanistic-empirical modeling have been employed by researchers (AASHTO, 1993, 2008; HRB, 1961). The deterioration models took both linear and non-linear forms such as sigmoidal models and survivor curves (Chen & Mastin, 2015). Multiple linear regression, stepwise regression, and reliability models were also practiced (Luo, 2014; Shahin et al., 1987). However, uncertainties involved in the deterioration of pavement such as traffic loading, material properties, and environmental impacts, vary highly randomly with time and thus many investigators concluded that the pavement performance should be governed as stochastic processes. In this direction, Markov chain models have been developed (Lethanh et al., 2015; Yang et al., 2006). Few other approaches included application of artificial intelligence such as expert systems, ANN, Genetic Algorithms (GA) and hybrid systems (Ismail et al., 2009; Kargah-Ostadi et al., 2015; Sundin & Braban-Ledoux, 2001).

The prediction models can be grouped on the basis of the predicted performance parameters as: primary response models, structural performance models, functional performance models, and damage models. The present study deals with the development of structural performance models. Data pertaining to the structural assessment of pavements is obtained nowadays with the use of

FWD. In spite of this, the prioritization projects for reconstruction or rehabilitation are primarily based only on visual identification of distresses and functional condition surveys (Papagiannakis & Masad, 2008). Due to the reasons stated earlier in performing FWD tests frequently, usage of structural parameters is not widespread during the selection of maintenance or repair decisions. Consequently, the pavement may demand substantial rehabilitation in future, which could have otherwise required only preventive maintenance. Therefore, to encourage the practice of using structural parameters at a larger scale approaches providing quick judgments regarding the deteriorated condition, and its possible reasons or layers contributing to the distress generation are obligatory.

Many efforts have been made by the researchers to find relatively quick alternative analysis methods and obtain a thorough knowledge of pavement condition, without performing rigorous testing and analysis. The application of deflection basin parameters which are FWD basin derived strength indicators, provides one such method of delivering rapid estimates of pavement's structural state. The commonly proposed DBP include surface curvature index, base curvature index, area under pavement profile, base damage index, base layer index, middle layer index, and lower layer index (Horak et al., 2015; Kim, 2000; Losa et al., 2008; Park et al., 2005; Xu, et al., 2002a, 2002b). The significance of using DBP has been highlighted in the study carried by Kim (2000) in which these estimates were used to empirically evaluate individual layer moduli of pavements without undergoing complex back-calculation schemes. More recent studies have also adopted these estimates of the deflection basin to analyze and report the condition of pavements (Fakhri & Dezfoulian, 2019; Rabbi & Mishra, 2019; Saleh, 2016; Sollazzo et al., 2017). In addition to this, researchers have also studied the impact of critical factors such as those related to structure and temperature on pavement responses using DBP (Xu et al., 2002a, 2002b). Surface distresses, and visual condition ratings were also reported to affect deflection parameters, but no analytical or mathematical model was presented to determine the relation (Horak et al., 2015). In similar works, functional performance rating indicators of pavements were studied for their correlation with structural indices (Fakhri & Dezfoulian, 2019). However, parameters such as environmental factors, traffic, and subgrade soil conditions also have leading impacts on pavement health, which are reflected in surface deflections and DBP. The inclusion of these diversified factors results in complicated pavement engineering problems, which are challenging to solve using closed-form solutions or physics-based principles (Li & Wang, 2018).

Analytical modeling using computational intelligence techniques find their wide application in such real-world problems (Majidifard et al., 2019; Shafabakhsh et al., 2015). Alavi & Buttlar (2018) adopted genetic programming to formulate prediction model for PCI and used smartphones to collect airport pavement condition data. Previous studies supported the usage of ANN for back-calculation of pavement layer moduli and dynamic moduli of asphalt layer when pavements were subjected to FWD load (Gopalakrishnan et al., 2014; Varma & Kutay, 2016; Zaabar et al., 2014). Researchers have also adopted a hybrid of ANN and GA to develop a back-calculation program and DBP were implemented to predict responses of asphalt pavements (Li & Wang, 2017, 2018). The integration of the AI approach and FWD derived parameters is found to be quiet successful in few studies (Fakhri & Dezfoulian, 2019; Sollazzo et al., 2017). The DBP surface curvature index and the thickness of the asphalt layer were adopted to predict tensile strain in asphalt pavements (Plati et al., 2015). Thus, popularity of predictive models is evident from the great success obtained using them in the field of pavement engineering. Being versatile, relatively little effort is required to adapt them to local conditions.

2.9. Research gaps

From the thorough review of literature, it is evident that several research works have been performed using various NDT technologies for delamination detection in asphalt pavements and concrete bridge decks, both in-field and simulation studies. Studies report that the success obtained using IRT in case of asphalt pavements is limited and accordingly, field studies are few. Moreover, most of the studies have utilized the method in a qualitative way and failed to provide its quantitative and objective estimates. Also, the detection time zone for passive thermography greatly varies, as reported by various researchers, which is not available in Indian context as seen from the literature. IRT has fair chances to become widespread in India owing to its quick and easy data collection abilities but requires increased reliability in measurements. It is therefore essential to assess the utility of IRT in asphalt pavements and develop a novel methodology for quantitative processing of its estimates that would ensure its accuracy. Additionally, for concrete bridge decks as well, studies on identification of delamination using IRT and its field inspection time duration for Indian conditions is lacking. Furthermore, many studies have adopted simulation framework rather than conducting in-field studies. Therefore, actual field studies on concrete bridge decks and an approach for their quantitative analysis is required to derive their field inspection capabilities.

Optimal allocation of funds necessitates a judicious approach to justify M&R necessities which could be accomplished in the most effective way using prioritization performed based on pavement condition. Several techniques of pavement prioritization for M&R implementations are reported in literature but no study tries to assess the impacts of such projects in achieving the intended goal of sustainable development. Therefore, it is vital to accelerate the pace of research in this regard by developing a robust methodological framework. The devised approach should consider various positive as well as negative impacts of M&R projects that would be contributive in improvising the current action plans. Moreover, it should be able to contemplate the uncertainties associated with judgments of experts and concerned decision-makers which may cause the imprecision in the estimation. Hence, research is needed to explore an integrated approach, from assessing the pavement condition to prioritizing them and assessing the impacts of M&R projects while incorporating uncertainty aspects in the judgments. Thus, framework developed using fuzzy-based MCDM, Strength-Weakness-Opportunity-Threat (SWOT) and its hybrid mechanisms upon actual field inputs of pavement condition offer a robust and strong basis, which is lacking in the present scenario.

The assumption which has been considered widely that judgment of M&R needs of pavements can be based on its functional health has become obsolete. Significance of appraising the structural health indicators has been strongly recognized by the highway agencies. India, being in the developing stage, often faces a shortage of funds which makes it difficult to frequently conduct deflection testing on such a huge network of pavements. As such, methods providing a quick assessment of the structural condition of pavements are limited. Among the available ones, they generally unaccounted major contributing parameters from the wide spectrum of deteriorating agents or employed non-intelligent approaches. Many of them also used data from any synthetic database rather than using actual field data. Thus, there is an immediate need to perform adequate research on endowing rapid estimates by employing tools of computational intelligence in pavement management systems and incorporating impacts from various deteriorating mechanisms.

2.10. Concluding remarks

In the present chapter, prospects of pavement management systems and bridge management systems were discussed with special focus on evaluation using N technologies. Also, various prioritization techniques and condition prediction models were reviewed. Based on this, research gaps were identified and discussed. These literature review investigations reflect that there is a need for an accelerated pace of research, which can deal and address different aspects of pavement and bridge management systems in an effective way. The crucial and fundamental findings of the contemporary research foster the development of a comprehensive and robust decision-support system for pavement management. The identified shortcomings motivated to investigate the following aspects for Indian conditions:

- To understand the cause-effect relationships of various deterioration mechanisms on the integrity of pavement and bridge infrastructure.
- To highlight the need for assessment of delamination and its adverse impacts on pavement and bridge infrastructure as well as to emphasize on its detection at early stages using quick estimation techniques.
- To explore the delamination detectability and ideal inspection times by employing infrared thermography technique not only qualitatively but also deriving its quantitative conjectures.
- To devise pavement prioritization approach using advanced fuzzy-based soft-computing techniques and overcome the subjective evaluations which are generally adopted due to scarcity of funds for comprehensive condition evaluation. Such approach impart comprehensive understanding about the pavement condition and provide deeper insights on inherent complexities arising from the biases induced in human judgements.
- To unveil the potential consequences of pavement maintenance projects and develop its managerial framework using integration of SWOT and fuzzy techniques by suggesting the best action plan and management policies, fulfilling long-term goals of sustainable development.
- To emphasize on the significance of appraising structural condition of pavements in decision-making exercises of pavement M&R and facilitating reliable structural performance prediction models using computational intelligence approach.

A rigorous attempt has been made in the present study to address the above-mentioned issues by providing suitable solutions in scientific and engineered ways.

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