VIRGINIA TECH

GUIDE FOR NETWORK-LEVEL FLEXIBLE PAVEMENT STRUCTURAL EVALUATION AND MANAGEMENT

TPF-5(385) Pavement Structural Evaluation with Traffic Speed Deflection Devices

TASK 3: DEVELOPMENT OF GUIDELINES ON HOW TO INCORPORATE PAVEMENT STRUCTURAL CONDITION DATA INTO THE PMS

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Guide for Network-level Flexible Pavement Structural Evaluation and Management

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ABSTRACT

An essential feature of a pavement management system (PMS) is periodic collection of pavement condition data to inform state highway agencies' decision making. Historically, pavement condition data has consisted of visual surface condition data (e.g., cracking and rutting) collected either manually or automatically using dedicated survey vehicles. Adding structural condition data may provide additional information to complement the already available surface condition data. Most state highway agencies have already implemented a PMS based on defined strategic goals. Agencies planning to incorporate structural condition data into the PMS will need to consider those goals and the right methods for incorporating the new information. Goals can also reflect the state legislature's defined expectations and guide the development of a PMS for the entire road network. Including structural condition data in the evaluation of pavement condition need not alter an agency's thinking and may instead enhance their efficacy in achieving strategic goals, potentially enabling more ambitious goals going forward.

The central function of a PMS is selecting and recommending treatment for pavement sections. Treatment selection depends on the recorded pavement condition, which typically has been based on surface condition only. Although the typical process has flaws, implementing a PMS has resulted in significant savings to highway agencies, and the recommended treatments are in many cases correct. Structural condition data can help improve treatment selection in cases where treatment recommendations based on surface condition alone are not sufficient; the structural condition data can further enhance or refine treatment selections based on surface condition data. This guide recommends this approach due to two advantages:

- Treatment selection based on pavement surface condition has been used for a long time. The process has been refined based on extensive historical data and agency in-house experience, resulting in an effective PMS that, for the most part, recommends appropriate treatment. Using structural condition data to further enhance the treatment selection process leverages the current process's strengths.
- Using structural condition data to augment the current process requires minimal resources for implementation and ensures that, if structural condition data can no more be collected due to budgetary reasons, the agency can revert to making decisions based solely on surface condition data.

Important aspects to incorporating pavement structural condition into the PMS:

- Defining collection and reporting procedures and setting quality assurance and quality control standards.
- Selecting the structural condition parameter(s) to use in the PMS.
- Defining thresholds of the selected structural condition parameter(s). Choosing appropriate thresholds is perhaps the most difficult part in effectively incorporating structural condition into the pavement management decision-making process. The thresholds are difficult to define because they directly affect the treatment selection process, and there is limited information regarding these thresholds. However, approaches based on national studies or based on data obtained from a falling weight

deflectometer can be used as a starting point. Ultimately, like many processes in pavement engineering, agency-specific threshold calibration is recommended as more experience is acquired.

- Implementing the process of including the structural condition defined by the selected parameter(s) into the decision-making process.

This document focuses on the last three points listed above, leaving the data collection procedures for state highway agencies to be reported in a separate document.

CHAPTER 1: GUIDE OVERVIEW

This guide presents approaches that state highway agencies can use to incorporate pavement structural condition information into the pavement management decision-making process at the level of the entire road network. Chapter 2 presents an overview of pavement management and the importance of the structural condition in determining the deterioration of pavement sections. Chapter 3 summarizes data collection procedures. Chapter 4 presents structural condition assessment methods that can be used to incorporate the structural condition into the pavement management system (PMS) and how structural condition thresholds can be established. The structural condition parameters discussed are the structural number (*SN*) and the deflection bowl index SCI300. Chapter 5 discusses implementation into a PMS.

CHAPTER 2: PAVEMENT MANAGEMENT

Introduction to Pavement Management

The American Association of State Highway and Transportation Officials (AASHTO) defines pavement management as “a set of tools or methods that assist decision-makers in finding optimum strategies for providing, evaluating and maintaining pavements in a serviceable condition over a period of time” (AASHTO, 1993). Pavement management has evolved to become a system-based approach for managing pavement performance. State agencies rely on PMS to manage and maintain their pavement assets. An efficient PMS should assist agencies in performing the following functions (AASHTO, 2012; Wolters et al., 2011):

- Providing a centralized location for pavement inventory.
- Assessing the current and future pavement condition.
- Analyzing the consequences of different investment levels on the pavement condition.
- Identifying pavement preservation and rehabilitation recommendations that optimize the use of available funds.
- Assisting as a decision-making tool in optimizing rehabilitation, maintenance, and trade-off options.
- Justifying and securing budget needs to elected officials and other stakeholders.

Pavement management supports agencies in the decision-making process at the strategic level, the network level, and the project level (AASHTO, 2012; Wolters & Zimmermann, 2008; Wolters et al., 2011). The characteristics of each level are presented below.

Strategic Level

At the strategic level, pavement management assists legislators, elected state officials, and administrators in determining pavement performance targets, determining funding levels to achieve those targets, and making long-term strategic decisions and policies. Effective pavement management should communicate effectively between the strategic, network, and project-level activities. Strategic-level decisions directly influence the maintenance and rehabilitation plans of the agencies. At the strategic level, decisions are not as detail-oriented compared to the other levels, and the information they are based on is more speculative. The impact of decisions made at this level is broad compared to network-level and project-level decisions.

Network Level

At the network level, pavement management helps asset managers and pavement management engineers to evaluate the overall needs of the entire road network, resulting in project and treatment recommendations for multi-year plans, and calculate the consequences of different investment strategies. Various pavement treatment strategies are selected at this level depending on the agency’s priorities and available funding. At this level, pavement management also helps the managers and engineers to select cost-effective treatments and identify where to recommend such treatments in the road network. Recommendations made at this level, in alignment with the strategic-level decisions, guide the project-level engineers in achieving the agency’s goals.

Network-level decisions are more detailed than those at the strategic level but less detailed than at the project level. The impact of decisions at this level is more focused than at the strategic level but broader than at the project level. Network-level decisions are made based on pavement condition data collected over the whole network. Most agencies currently use automated surface distress surveys to collect this condition data. Therefore, most agencies, with few exceptions and on a subset of the network, currently do not use structural condition data in their network-level PMS.

Project Level

At the project level, pavement management helps design and construction engineers select maintenance activities for the current year, select materials for maintenance and rehabilitation activities, and design pavement thicknesses for rehabilitation. Ideally, project-level decisions are based on the recommendations made at the network level. The project-level decisions are focused over a short time frame and involve working with data that is more detailed, such as nondestructive structural condition testing coring, and material testing. The project-level decisions are more detailed and constitute the final treatment selection.

Importance of Pavement Structural Evaluation for Network-level Pavement Management

The most important aspect of pavement design is determining the layers and thicknesses needed to carry the structural traffic loading. Therefore, the pavement structural condition is a key parameter in determining pavement deterioration and designing appropriate cost-effective treatments.

Causes of Pavement Deterioration

Pavements are designed to structurally carry the traffic load (reduce stresses on the subgrade) and to provide a safe and smooth riding surface. The structural condition plays a major role in the capacity of the pavement to perform as required on all aspects: structural, safety, and ride. Environmental conditions (most importantly, climatic factors) also play a significant role. In general, a deteriorating structural condition will enhance the negative environmental effects on the pavement sections, which in turn contributes to accelerating the structural deterioration. The following are some causes of pavement deterioration:

i) Traffic: Traffic is one of the most influential factors in pavement deterioration (Adlinge & Gupta, 2013; Almeida et al., 2019; Henning et al., 2014). Traffic repeatedly applies load to the pavement, which eventually leads to pavement deterioration. The impact of traffic on pavement deterioration goes beyond just the number of cars traveling on the road; it also includes different traffic types (such as trucks and buses), allowable loads, tire pressures, etc. Load-related cracking and rutting are two of the main distresses that occur due to repeated traffic loading.

ii) Climatic factors:
   a. Temperature Variation: Temperature variations can affect the entire pavement structure. For flexible pavements, temperature affects the modulus of the bituminous layer, which changes the stress and strain distributions in the

pavement. Furthermore, low temperatures lead to volumetric contraction of the asphalt concrete (AC) material, which can result in the development of thermal cracks. Extremely low temperatures also affect the pavement base and subgrade material properties, causing contraction of the entire pavement structure that results in transverse cracking. An increase in the pavement temperature makes it susceptible to distresses such as rutting and bleeding.

b. Moisture: Moisture has a significant impact on the strength of the pavement layers. Rainfall can lead to erosion, elevation of the ground water table, pumping, and infiltration. All these factors subject the pavement to adverse conditions that cause pavement deterioration. Once the water infiltrates into the pavement layers, it can move freely within channels of connected void. The water can also take away the fine aggregates within the pavement layer with the application of repeated loads. The water within the pavement wets the layers' materials and reduces their strength, which in turn reduces the overall bearing capacity of the whole structure. If the water is trapped in isolated voids of the AC layer, the resulting excess pore water pressure can accelerate the stripping of the asphalt film and result in raveling or potholes (Wang et al., 2017). In the case of rigid pavements, water infiltrating into the joints and cracks of the pavement can lead to mud pumping under the action of repeated loading, which rapidly increases the rate of pavement deterioration.

c. Freeze-thaw cycles: When the pavement freezes, it gains strength. However, when the pavement thaws and the ice melts, the pavement strength dramatically decreases. The excess water must be properly dissipated to prevent moisture-related problems in the subgrade (Chamberlain et al., 1979; Qiao et al., 2013). Even if the water is properly dissipated from the pavement structure, the freeze-and-thaw cycles could still leave voids in the pavement structure that can aggravate the pavement deterioration. In rigid pavements, freeze-thaw cycles can result in durability cracking. A higher number of freeze-thaw cycles can cause significant loss of pavement smoothness (Titus-Glover et al., 2019).

Rate of Pavement Deterioration

The general shape of the pavement deterioration curve is described as an "S"-shaped curve (Beckley, 2016). Initially, new pavement deteriorates slowly, but once it reaches a certain stage where various surface distresses appear on the pavement, the rate of deterioration starts to accelerate rapidly. Various state agencies use preventive maintenance practices to slow the deterioration rate. For example, sealing the surface distresses can reduce water infiltration and retard future deterioration. However, preventive maintenance practices only restore the pavement's functional condition without making significant improvements to the pavement's structural condition. Therefore, such practices generally do not improve structurally weak pavements.

In general, deterioration in a pavement structure can be classified as functional or structural. It is important to recognize what type of deterioration is occurring since the appropriate treatments depend on whether the deterioration is primarily functional or structural. Although this suggests that the two types of deterioration are different, they are not completely independent. The structural condition is a significant factor that directly influences the rate of deterioration of the functional condition. Also, improperly sealed cracks allow water infiltration and accelerate the rate of structural deterioration. Pavement deflection testing and/or coring is performed to determine if the main cause of pavement deterioration is structural or functional. Thus, network-level pavement structural condition can provide valuable information to determine the causes of pavement deterioration and predict future pavement condition.

CHAPTER 3: NETWORK-LEVEL STRUCTURAL CONDITION DATA COLLECTION

Good quality data is essential to successfully evaluate the pavement structural condition. Important aspects of data collection include 1) establishing a data quality management plan (DQMP), 2) defining the data to be collected, and 3) establishing supporting data that could be collected.

DQMP

A DQMP defines what constitutes acceptable data and the data collection process. The plan includes quality control procedures and acceptance criteria as defined by the agency. The DQMP should reflect the agency's intended use of the collected data. Key features of the DQMP include:

- Defining data collection procedure
- Establishing data quality standard
- Identifying responsibilities
- Defining personnel training requirements
- Defining equipment calibration and method of acceptance
- Establishing data inspection procedures
- Establishing corrective actions
- Establishing method of management reporting

The DQMP is an integral part of successful data collection and is usually an agency-specific document that affects more than the PMS. A good DQMP ensures that the collected data is appropriate for supporting the implementation of network-level structural condition data into the PMS.

Collected Data

Device Calibration, Certification, and Verification

To ensure good quality data, it is essential that the data collection device is calibrated and independently certified. This will ensure that the data collected satisfies industry-accepted accuracy and precision requirements. These requirements are generally established based on the current state of the technology and the accuracy and precision required for effective use of the collected data. For example, structural condition data can be used to determine the required overlay thickness needed for the pavement to perform adequately for a required period. The accuracy and precision of the collected data needs to be at a level where the accuracy and precision of the determined required overlay thickness is within a certain level, such as 2 inches for network-level applications.

While calibration and certification procedures adjust the device so that the collected data is within acceptable accuracy and precision requirements, verification procedures ensure that the device is still operating within calibration range (i.e., that the calibration is still valid). In general, verification procedures are set by the service provider and agency and are performed at regular time intervals agreed to by the service provider and agency.

Spatial Resolution of Collected Data

The smallest section length considered in a PMS is generally 0.1 miles. Therefore, the structural evaluation data collected should be at a spatial resolution of at least 0.1 miles. Data collected from traffic speed deflectometer devices (TSDDs), such as the traffic speed deflectometer (TSD), has generally been reported at 10 to 16 m (0.00625 to 0.01 miles). This is adequate for most applications on flexible pavements. However, there are network-level applications, such as evaluation of joints in jointed concrete pavements, that require a spatial resolution in the order of 1 m or lower. Therefore, the spatial resolution of data collection should be specified according to the desired use of the collected data.

Pavement Response to Loading

The pavement's response to loading is critical data collected during structural pavement evaluation. Because loading is dynamic, the applied load during testing should also be measured along with the pavement response. The pavement response should be measured at appropriate locations to perform adequate structural evaluation of the pavement. In general, this requires measurement of the pavement response at various distances from the applied load so that the structural condition of the various pavement layers and the subgrade can be evaluated. The traditional pavement response in structural evaluation is pavement deflection, but related responses such as pavement deflection slope can also be used.

Environmental Conditions and Temperature Data

Environmental conditions can significantly affect the pavement's structural response. Surface and air temperature have a significant effect on the response of flexible pavements and therefore should be recorded during testing. Similarly, seasonal changes can also significantly affect the structural condition of the pavement. Excessive moisture in the pavement structure weakens the pavement, resulting in higher deflections. Freezing makes the pavement structure stiffer, resulting in lower deflections. Thawing releases the trapped moisture saturating the pavement structure, thus making the pavement weak and resulting in higher deflections. Although not directly measured, seasonal changes can be inferred from the date of testing.

Supporting Data

Layer Thicknesses

Pavement layer thicknesses are generally not collected during network-level structural evaluations. However, the pavement layer thicknesses play a major role in analyzing and interpreting the results of the structural condition assessment. For example, layer thicknesses are needed to (a) perform temperature correction for data collected on flexible pavements, (b) calculate the effective structural number (SN_{eff}), (c) back-calculate the layer moduli, and (d) determine the structural condition of specific layers in the pavement. Therefore, layer thickness information is necessary for a detailed analysis or mechanistic analysis of the structural response. If layer thicknesses are not available, the structural information collected can still be used in the PMS but in a more empirical way, as detailed in Chapter 4.

Previous Day Temperature

The previous day's temperature is needed to perform temperature correction. The previous day's temperature can be obtained from readily available national weather databases.

CHAPTER 4: STRUCTURAL CONDITION ASSESSMENT

For structural condition assessment, a structural condition index (or multiple indices) should be selected based on the agency's pavement management needs. The following are factors to consider in selecting the index:

- Current pavement structural assessment methods used by the agency for project-level analysis.
- Ease of computation of the index for network-level applications.
- Availability of supporting data, such as pavement layer thicknesses.
- Intended use of the index in the PMS.
- Evaluated and recommended indices from published research.

Possible indices range from raw measurements obtained from the device (e.g., deflection slopes from the TSD) to layer moduli obtained from viscoelastic back-calculation procedures. However, most realistic indices are based on deflection bowl indices (difference between deflections) that target the structural condition at specific depths in the pavement (e.g., surface curvature index 300 [SCI300]) or the effective structural number (SN_{eff}) used in the AASHTO overlay design procedure. This chapter discusses temperature correction, calculation of structural parameters, and determining thresholds for the structural parameters. The parameters presented are subgrade resilient modulus (M_r), effective structural number (SN_{eff}), required structural number (SN_{req}), design structural number (SN_{design}), and surface curvature index 300 (SCI300).

Temperature Correction

Temperature correction of deflection measurements is important for flexible pavements because the response of the asphalt layer depends on temperature. Temperature correction is performed in two steps and requires knowledge of layer thicknesses (at least the asphalt layer thickness). The first step is to determine the temperature at the mid-depth of the asphalt layer. The second step is to perform a correction of the relevant measurement. The BELLS3 equation is the most widely used equation to determine the asphalt layer mid-depth temperature. To calculate the SN_{eff}, the AASHTO procedure requires correction of the maximum deflection, which generally coincides with the deflection under the load d_0. For the surface curvature index SCI300, Nasimifar et al. (2018) developed a correction procedure for measurements obtained from a TSDD.

BELLS3 Mid-Depth Temperature Equation

The BELLS3 equation is given by

$$T_d = 0.95 + 0.892 \times IR + [\log(d) - 1.25] \times \left[-0.448 \times IR + 0.621 \times T_p + 1.83 \times \sin(hr_{18} - 15.5)\right] + 0.042 \times IR \times \sin(hr_{18} - 13.5) \tag{1}$$

Where

T_d = Pavement temperature at depth d, °C
IR = Pavement surface temperature, °C
d = Depth at which mat temperature is to be predicted, mm
T_p = Average air temperature for the previous day (the day before testing), °C

sin = Trigonometric sine function on an 18-hour clock system, with 2π radians equal to one 18-hour cycle
hr_{18} = Time of day in a 24-hour clock system, but calculated using an 18-hour AC temperature rise-and-fall time cycle

AASHTO 1993 Temperature Adjustment Procedure for Maximum Deflection D_0

AASHTO pavement design guide (AASHTO, 1993) provides the temperature correction procedure for the maximum deflection (D_0), measured by the falling weight deflectometer (FWD). The temperature adjustment factor is based on the ratio of the predicted deflections as shown below:

$$T(t) = \frac{d_0(68)}{d_0(t)} \tag{2}$$

Where
$T(t)$ = temperature adjustment factor
$d_0(68)$ = d_0 at 68°F
$d_0(t)$ = d_0 at testing temperature t, °F

The temperature adjustment factor can be obtained from Figure 1, using the total asphalt thickness and the AC mix temperature at the time of deflection testing. Although this method was developed for deflection from the FWD, many studies have used the temperature correction method for measurements from continuous deflection devices with deflection normalized to a load of 9,000 lb (similar to that from the FWD).

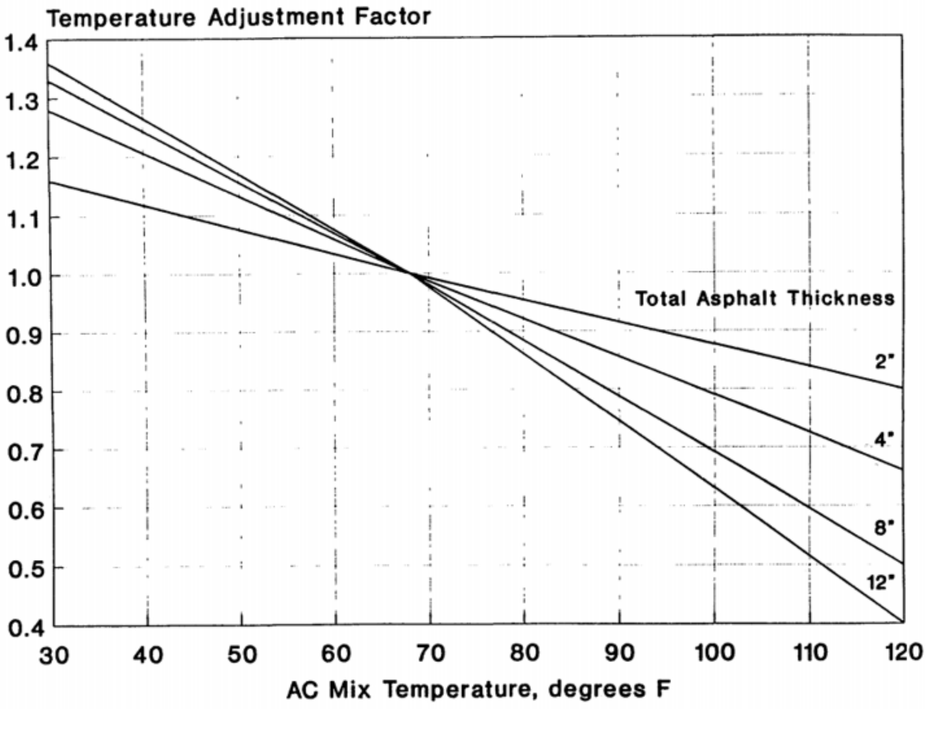

Figure 1. D_0 correction for AC mix temperature for granular and asphalt treated base pavements (AASHTO, 1993).

Temperature Adjustment Procedure for Surface Curvature Index SCI300

Nasimifar et al. (2018) developed an approach to correct the surface curvature index (SCI300) measured from the TSD for temperature variations. The model improves on the stiffness adjustment model developed by Rada et al. (2016) by including viscoelastic considerations as well as the asphalt layer thickness. The temperature adjustment factor is based on the relationship between 1) SCI300 and the tensile strain at the bottom of the asphalt layer, 2) the tensile strain at the bottom of the asphalt layer and the dynamic modulus of the asphalt layer, 3) the asphalt layer thickness, and 4) the latitude of the tested location. The temperature correction factor is calculated as follows:

$$\lambda = \frac{SCI_{Ref}}{SCI_T} = \frac{10^{-0.05014T_{Ref}+0.019049T_{Ref}\log(h_{AC})\log(\varphi)}}{10^{-0.05014T+0.019049T\log(h_{AC})\log(\varphi)}} \tag{3}$$

Where
λ= Temperature Adjustment Factor
SCI_{Ref}= Adjusted SCI300 at a reference temperature
T_{Ref} = Reference temperature in °C
h_{AC} = Asphalt layer thickness, mm
T = Mid-depth AC layer temperature at the time of measurement in °C
φ = Latitude of the location of measurement (within 30 to 50 degrees)

Calculating Structural Parameters

Deflection Bowl Indices

Deflection bowl indices originated from structural pavement evaluation with the FWD (Horak, 1988; Thompson & Hoffman, 1983) and have been adopted for TSDDs. Rada et al. (2016) evaluated 77 deflection bowl indices that can be calculated from TSDD measurements to find which indices best correlate with the tensile strain at the bottom of the asphalt layer and the compressive strain at the top of the subgrade using simulated deflection bowls. Notable among the 77 indices are the ones called surface curvature indices (SCI_r) and deflection slope indices ($DSI_{s\text{-}r}$) given by

$$SCI_r = D_0 - D_r \tag{4}$$

$$DSI_{s-r} = D_s - D_r \tag{5}$$

Where
r, s = distance from applied load in inches ($s < r$)
D_x = deflection at distance x from the load
Note that for $s = 0$, $DSI_{0\text{-}r} = SCI_r$

Some of the indices given in the equations above are well known. For example, SCI300 (or SCI12) is obtained from Equation 4 with r set at 300 mm (12 inches). Similarly, the base damage index and base curvature index of Horak (1988) correspond to $DSI_{12\text{-}24}$ and $DSI_{24\text{-}36}$, respectively. The function of deflection bowl indices is to assess the structural condition within a depth of a pavement mostly restricted to depths between s and r, the subscripts in the *DSI* equation (for *SCI*, *s* = 0), which is based on the simplifying assumption of a 1-to-1 slope of stress distribution within the pavement.

General guidelines for the use of deflection bowl indices are as follows:

- SCI_r or $DSI_{s\text{-}r}$ with *r* values below 12 inches are good indicators of the condition of the asphalt layer and correlate well with the tensile strain at the bottom of the asphalt layer.
- $DSI_{s\text{-}r}$ with *s* values greater than 24 inches are good indicators of the condition of the subgrade and correlate well with the compressive strain on top of the subgrade.
- $DSI_{s\text{-}r}$ with *s* values between 8 inches and 24 inches are good indicators of the condition of intermediate layers between the asphalt layer and the subgrade.

The general guidelines given above can be further refined based on layer thicknesses and composition information, if available. For example, if the asphalt layer is known to be 8 inches thick, then, based on the 1-to-1 slope of stress distribution assumption, SCI_8 should be used to evaluate the asphalt layer.

Structural Number and Resilient Modulus

AASHTO 1993 Effective Structural Number and Resilient Modulus Calculations

The SN_{eff} based on the AASHTO method for overlay design is calculated as follows:

$$SN_{eff} = 0.0045 H_p \sqrt[3]{E_p} \tag{6}$$

Where E_p is the effective modulus of pavement layers determined from the following equation:

$$D_{max} = 1.5 \times p \times a \left\{ \frac{1}{M_r \sqrt{1 + \left(\frac{H_p}{a} \sqrt[3]{\frac{E_p}{M_r}} \right)^2}} + \frac{\left[1 - \frac{1}{\sqrt{1 + \left(\frac{H_p}{a} \right)^2}} \right]}{E_p} \right\} \tag{7}$$

Where

p = contact pressure (psi),

a = circular load radius (inches),

H_p = total pavement layer thickness (inches),

D_{max} = maximum deflection in (inches),

and the subgrade modulus used in Equation 7 is determined as follows:

$$M_r = \frac{P(1 - \mu^2)}{r \times \pi \times d_r} \approx \frac{0.24P}{r \times d_r} \tag{8}$$

Where
P = applied load (lb)
d_r = measured deflection (inches)
r = distance between the load center and the point where deflection is measured (inches)
μ = Poisson's ratio (generally assumed to be 0.5)

For network-level applications with data collected using a TSDD, D_{max} is often approximated by D_0. This results in slightly underestimating SN_{eff} (depending on the viscoelastic time delay between D_{max} and D_0).

Rohde Equation Effective Structural Number Calculations
The Rohde equation (Rohde, 1994) was developed using a large database of the simulated response of different pavement configurations (number of layers and layer thicknesses). Nasimifar et al. (2019a, 2019b) used pavement structures simulated with 3-D MOVE to recalibrate the Rohde equation constants to account for the viscoelastic lag in the measurements obtained from TSDDs. The equation to calculate SN_{eff} is given by:

$$SN_{eff} = C_1 SIP^{C_2} Hp^{C_3} \tag{9}$$

Where
SIP = structural index of pavement (µm)
Hp = total pavement thickness (mm)
C_1, C_2, and C_3 = coefficients for different surface types; for AC pavement the original coefficients are 0.4728, -0.4810, and 0.7581, respectively. The recalibrated coefficients of Nasimifar et al. (2019a) are 0.4369, -0.4768, and 0.8182, respectively.

SIP is calculated as follows:

$$SIP = D_0 - D_{1.5Hp} \tag{10}$$

Where
D_0 = temperature corrected peak deflection (see Nasimifar et al., 2019a) measured under a standard 9,000-lb load
$D_{1.5Hp}$= deflection measured at an offset of 1.5 times Hp under a standard 9,000-lb load
Hp = total pavement thickness in inches

Establishing Index(es) Thresholds to Determine Structural Condition Categories

Defining Structural Condition Categories

Structural condition categories are used to define the appropriate action in the treatment selection process based on the calculated structural index. In general, three to five categories can be defined, based on the agency's preference. In the case of five categories, these are generally used to define structurally Very Weak (Category 1), Weak (Category 2), Fair (Category 3), Strong (Category 4), and Very Strong (Category 5) pavements. In the case of three defined categories, the categories Very Weak and Very Strong are omitted. The number of thresholds that need to be established is one less than the number of structural condition categories. In the example of three structural condition categories, two thresholds need to be defined: one between Weak and Fair and another between Fair and Strong. Thresholds can be established using different methods:

- Expert knowledge and historical concepts
- Statistical concepts
- Engineering and mechanistic-empirical concepts

The approach used to establish the threshold should align with the agency's strategic goal. However, a good practice is to verify the established thresholds with other methods. For example, if thresholds are established based on a mechanistic-empirical approach, it is advisable to make sure that the percentage of pavement sections falling in each of the defined structural categories based on the thresholds is reasonable (statistical check) and obtain feedback from agency experts on the reasonableness of the thresholds.

Establishing Thresholds Based on Expert Opinion

Highway agency personnel's experience with deflection testing (generally acquired from FWD testing) can be leveraged to establish thresholds between Weak and Fair and Fair and Strong pavement sections. However, when thresholds are defined this way, it is important to note that there are differences between the FWD and TSDDs; thresholds based on experience gained from FWD testing are not as reliable when used with TSDD measurements as they are when used with FWD measurements (see Zhang et al., 2022). Therefore, although this approach could be used to establish the thresholds, it is recommended that it be used as a check on thresholds established using one of the other two methods rather than as the primary method of establishing thresholds.

Establishing Thresholds Based on Statistical Concepts

Establishing thresholds based on statistical concepts can involve very simple statistical concepts or more advanced concepts such as those based on artificial intelligence and machine learning concepts. In terms of data used to establish thresholds, statistical methods can be divided into two categories:

- Category 1: Methods based solely on the collected structural condition data.
- Category 2: Methods that use additional pavement characteristics and condition data along with the collected structural condition data.

For the first category of methods, the simplest statistical concept is to define thresholds based on percentile. For example, when three structural condition categories are used, thresholds could be defined so that 25% of the sections are classified as Weak, 50% are classified as Fair, and the remaining 25% are classified as Strong. The main disadvantage of this approach is its arbitrariness. It could be that the structural condition on all measured sections is adequate and the sections should all be classified as Strong. Therefore, it is essential to apply this approach to a representative sample of the network and to use expert opinion to determine what percentiles to use. Plotting the cumulative distribution of the measured sections' structural condition and observing locations of significant changes (such as slope) in the distribution can sometimes help determine the appropriate percentiles. Another factor to consider is using different thresholds for different road categories or for roads with different traffic (truck traffic) levels.

The second category of statistical methods uses additional pavement surface condition data to develop thresholds to classify the structural condition. This can be done if historical pavement surface condition and treatment data is available in the PMS. The approach consists of determining how the pavement structural condition affects the rate of deterioration of the pavement surface. Figure 2 shows how the pavement structural condition affects the rate of deterioration of load-related distresses (LDR), an index on a scale of 0 to 100 (100 being new), on three interstate roads in Virginia over a period of 8 years since the last treatment was applied (Katicha et al., 2020). The average deterioration of the LDR follows the thick black line, and the shaded area represents how the deterioration is affected by the structural condition (in this case, SCI300). The green shade represents the strongest pavement sections while the red shade represents the weakest pavement sections. The deterioration equation in this case is given by

$$LDR = 100 - \exp\{\beta_0 + \beta_1 \log(Age) + \beta_2 \log(Age) \times SCI300\} \tag{11a}$$

$$LDR = 100 - \exp\{\beta_0 + \beta_1(1 + \beta_3 SCI300)\log(Age)\} \tag{11b}$$

Where
LDR = load-related distress
Age = pavement age calculated as the difference between the year when the LDR is observed minus the year of the last applied treatment recorded in the PMS
SCI300 = surface curvature index
β_0, β_1, β_2, and β_3 = regression coefficients, with $\beta_3 = \beta_2/\beta_1$

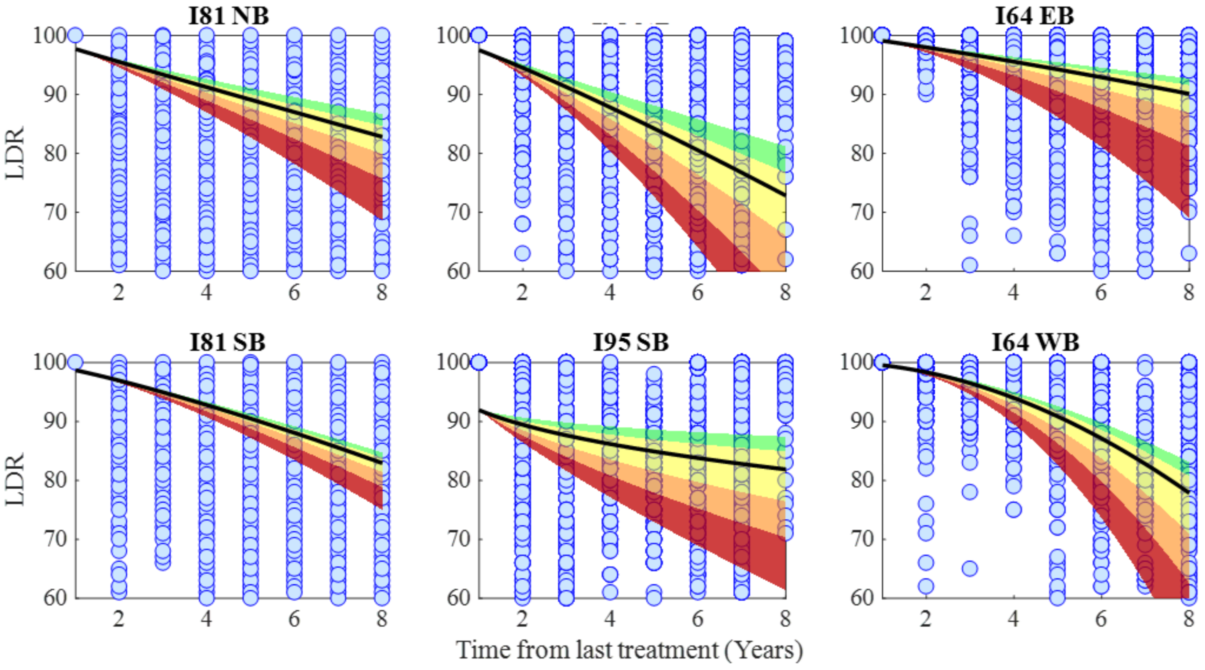

Figure 2. Effect of pavement structural condition on the rate of deterioration of LDR on three interstate roads in Virginia.

A possible approach to defining thresholds using Equation 11 is to select an acceptable level of LDR, LDR_T, and define the thresholds based on the time it takes for a pavement at an LDR level of 100 to reach LDR_T. For example, if an agency wants to define structurally Fair sections as sections where overlays last at least 4 years in a condition of $LDR_T = 70$ or better (hence Weak sections will have lower LDR after 4 years), then Equation 11 can be used to determine the corresponding SCI300 threshold to differentiate between Weak and Fair structural condition. A similar approach can be used for the threshold between Fair and Strong. This approach of using historical pavement surface deterioration data addresses the drawbacks of the first category approach of establishing thresholds based solely on percentile.

Establishing Thresholds Based on Engineering and Mechanistic-Empirical Concepts

Engineering or mechanistic-empirical concepts are used in the structural design and rehabilitation of pavements. Pavements are designed to carry a specific number of load repetitions before failing. Therefore, thresholds can be set based on how many load repetitions the pavement can carry before failing. For example, if the SN_{eff} is used as a structural index, then thresholds could be determined based on the required structural number (SN_{req}) or the built structural number (SN_{built}). If the deflection bowl indices are used, then these can be related to strains in the various pavement layers from which the number of load repetitions to failure can be obtained. These concepts are illustrated in the next three subsections.

Thresholds Based on SN_{req}

The SN_{req} is determined based on the total truck traffic (in terms of equivalent single axle loads [ESAL]) that the pavement needs to carry before failing (with other parameters such as the subgrade resilient modulus). The total ESAL can be determined from the average daily ESAL and the chosen design period, taking into account possible traffic growth (e.g., 20 years), as follows:

$$\log(ESALs) = z_R s_0 + 9.36\log\left(SN_{req}+1\right) + \frac{\log\left(\frac{p_0 - p_t}{2.7}\right)}{0.4 + \frac{1094}{\left(SN_{req}+1\right)^{5.19}}} + 2.32\log(M_r) - 8.27 \qquad (12)$$

Where

$ESALs$ = number of equivalent 18-kip single axle loads during the design period

z_R = standard normal z-value (based on functional classification of road)

s_0 = standard deviation (usually 0.45)

p_0, p_t = initial and terminal serviceability. Default for $p_0 = 4.2$

M_r = subgrade modulus [PSI] calculated from Equation 8

Thresholds to delineate between Strong and Fair and Fair and Weak can be determined based on the relative value of the SN_{eff} compared to the SN_{req}. A possible example is given below:

- Strong: $SN_{eff} > 0.7\ SN_{req}$
- Fair: $0.3\ SN_{req} \le SN_{eff} \le 0.7\ SN_{req}$

- Weak: $SN_{eff} < 0.3\ SN_{req}$

Another possible approach is to base the thresholds on remaining structural design life. For example, based on the AASHTO flexible pavement design equation, AASHTO provides a deterioration equation for *SN* as a function of time given by (see Figure 3):

$$\frac{SN_{eff}}{SN_{req}} = \left(\frac{RL}{DL}\right)^{0.165} \tag{13}$$

Where *RL* is the remaining life and *DL* is the design life. Note that by the time $SN_{eff} \approx 0.5\ SN_{req}$ (or SN_{design}), the pavement can be considered to have essentially failed. Thresholds could be defined as follows (here we show four categories):

- Strong: $RL/DL > 0.5$
- Fair: $0.25 \leq RL/DL \leq 0.5$
- Weak: $0.1 \leq RL/DL < 0.25$
- Very Weak: $RL/DL < 0.1$

For the typical 20-year design period, these correspond to

- Strong: $RL > 10$
- Fair: $5 \leq RL/DL \leq 10$
- Weak: $2 \leq RL/DL < 5$
- Very Weak: $RL/DL < 0.1$

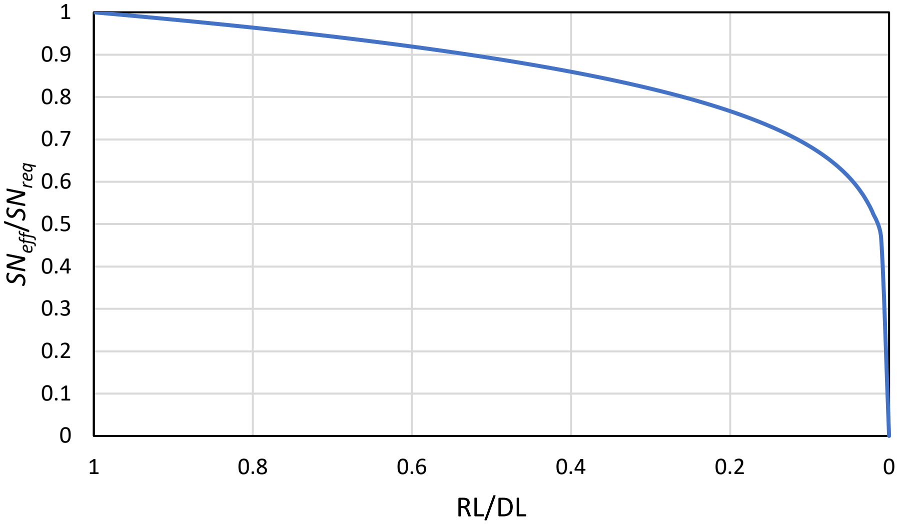

Figure 3. Relationship between remaining life and structural number.

The AASHTO equation implies that SN_{eff} reaches zero at the end of the design life. This seems unrealistic as the pavement should still provide some structural support (the asphalt layer could be considered to act as a granular layer). Therefore, AASHTO implements a modified equation given by (see Figure 4):

$$\frac{SN_{eff}}{SN_{req}} = 1 - 0.7\exp\left[-\left(\frac{RL}{DL} + 0.85\right)^2\right] \tag{14}$$

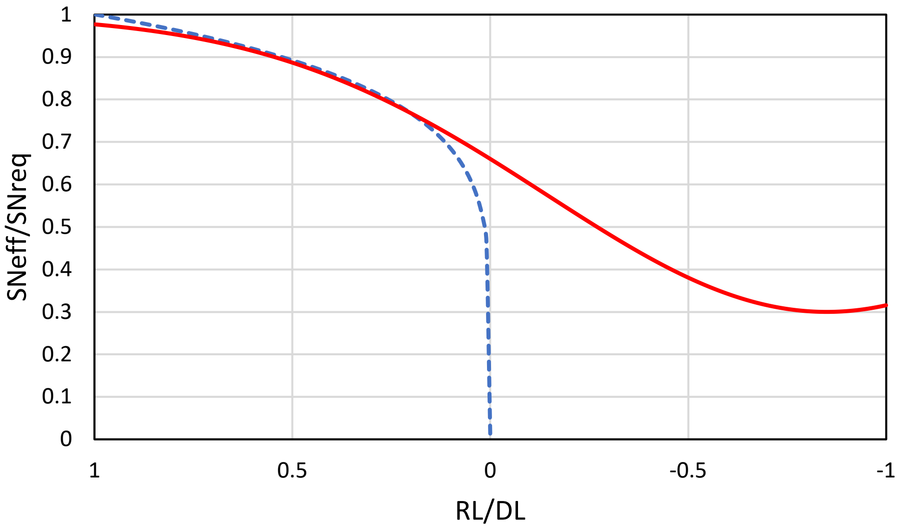

Figure 4. AASHTO equation and modified equation.

The modified equation reflects that at failure, the pavement still provides some structural capacity. Even after failure, the structural number continues to decrease even though after *RL/DL* < -0.85, the equation predicts an increase in *SN*. This could be modified by setting *SN* at *RL/DL* < -0.85 equal to *SN* at *RL/DL* = -0.85.

Thresholds Based on SN_{built}

The SN_{req} compared to the SN_{eff} can, in some instances, be a misleading indicator of the pavement structural condition. For example, the traffic used to calculate the SN_{req} is usually the current traffic. This could be different than the actual traffic when the pavement was designed and constructed. Another example where the SN_{req} can be misleading is when the pavement is built to carry more than the required traffic. This can happen if the subgrade resilient modulus varies but the built pavement is the same, usually based on the lower values of the subgrade resilient modulus. This could result in $SN_{built} > SN_{eff} > SN_{req}$. While $SN_{eff} > SN_{req}$ suggests the pavement is essentially better than a new pavement, the fact that $SN_{built} > SN_{eff}$ suggests that the pavement layers are actually not new and could perhaps have significantly deteriorated. That is, the layer coefficient has decreased compared to if the layers were new. Because pavement design, especially the design based on *SN*, is still a very empirical process, it is not clear which criterion between $SN_{eff} > SN_{req}$ and $SN_{built} > SN_{eff}$ should be the deciding factor, and perhaps the more critical one should be selected. Defining thresholds based on SN_{built} could be done similarly to how thresholds were obtained based on SN_{req}. However, with SN_{built}, the traffic is not required. To calculate SN_{built}, the layer thicknesses and design layer coefficients can be used.

Thresholds Based on Deflection Bowl Indices

The AASHTO design procedure using the *SN* concept is an empirical design procedure based on the AASHTO road test and, hence, engineering experience. The *SN* only considers the vertical stress and strain on the top of the subgrade to limit the subgrade permanent deformation as the design parameter; it does not include load-related stresses and strains in the pavement, which can also lead to structural distresses. An alternative to the *SN* is the use of deflection bowl indices. There are multiple indices that relate to various strains of interest in the pavement layers that are critical to the structural performance of the pavement. As an example, the SCI300 (or SCI12) has been related to the tensile strain at the bottom of the asphalt layer, and $DSI_{24\text{-}r}$ has been related to the vertical strain on top of the subgrade (Rada et al., 2016). Therefore, these indices can be used as structural indicators, and thresholds between structurally Strong and Fair and between Fair and Weak can be defined based on these parameters. The methodology is based on the number of remaining ESALs that the pavement can carry before failure. The failure could be fatigue cracking failure in the case of SCI300 or subgrade permanent deformation failure in the case of $DSI_{24\text{-}r}$. The approach was developed in Rada et al. (2016) based on several simulated pavement structures (with a moving load similar to the TSD). Given a measured SCI300 value, the approach is given as follows:

$$\varepsilon = a(SCI300)^b \tag{15}$$

$$E = c(\varepsilon)^d \tag{16}$$

$$N_f = C \times 0.00432\left(\frac{1}{\varepsilon}\right)^{3.291}\left(\frac{1}{E}\right)^{0.854} \tag{17}$$

Where *a*, *b*, *c*, and *d* are constants determined by Rada et al. (2016), with *a* and *b* depending on the asphalt layer thickness. *C* is the calibration constant (13.3 for interstate and primary roads and 18.4 for secondary roads) corresponding to the failure criteria of 10% and 45% of wheel-path cracking, respectively (Finn et al., 1977), for the fatigue equation of the Asphalt Institute (1982). Thresholds for three road categories—interstate, primary, and secondary roads—based on asphalt layer thickness are shown in Table 1 (see Katicha et al., 2017).

Table 1. Thresholds for SCI300 (TSD) and DSI

Road Category	**AC layer thickness, inches**	**Annual Traffic, million ESAL**	**Threshold for Fatigue Cracking at Wheel Path, %**	**Threshold for Poor**			**Threshold for Fair**		
				N_f, million ESAL	**SCI300, mil**	**DSI, mil**	**N_f, million ESAL**	**SCI300, mil**	**DSI, mil**
Interstate	> 9	1.4	10	2.8	3.7	3.0	7.0	2.7	2.2
Primary	6 - 9	0.2	10	0.4	6.2	5.2	1.0	4.9	4.0
Secondary	3 - 6	0.07	45	0.14	9.7	7.7	0.35	7.3	5.8

The thresholds in Table 1 are based on the following default ESAL values, which can be modified for specific applications:

- Interstate: 1.4 million ESAL, equivalent to about 6,500 annual daily truck traffic (ADTT; or 2,000 singles, 4,000 doubles, and 500 trains or triples)
- Primary: 0.2 million ESAL, equivalent to about 950 ADTT (or 700 singles, 220 doubles, and 30 trains or triples)
- Secondary: 0.07 million ESAL, equivalent to about 375 ADTT (or 300 singles, 75 doubles).

Thresholds were set so that a pavement with 2 years or less of life remaining is considered Weak, between 2 and 5 years is considered Fair, and 5 or more years is considered Strong.

CHAPTER 5: IMPLEMENTATION OF STRUCTURAL CONDITION INTO PMS

Most highway agencies already use a PMS based on surface condition. The PMS reflects the agency's goals, as well as federal requirements (such as the Highway Pavement Monitoring System [HPMS], MAP-21, and FAST Acts requirements). It is therefore important that any added structural condition as a parameter in the PMS reflects these goals and requirements. The structural condition can be used in the PMS with the following items:

1. Delineate Weak, Fair, and Strong sections.
2. Identify sections that are good candidates for preservation treatments and those that are likely to need major rehabilitation.
3. Determine required overlay thickness.
4. Modify treatments selected based on surface condition.
5. Develop improved pavement deterioration models.
6. Perform a pavement needs analysis.
7. Determine budget needs.
8. Optimize resource allocations.

Depending on an agency's overall goals, any single or combination of the activities listed above can be used. Furthermore, these activities are not necessarily mutually exclusive, as presented in the following subsections. In this chapter, we discuss the first four items, with emphasis on the third and fourth. The fifth item was briefly discussed in Chapter 4. In general, implementation of the last three items is not explicitly affected by incorporation of the structural condition and therefore is not discussed in this document.

Delineate Weak, Fair, and Strong Sections

Delineating Weak, Fair, and Strong sections can be used to track the structural performance of the pavement for inclusion in a state-of-pavement report. These sections can be used to determine the percentage of pavement in each structural condition category. Agency goals can be used to set minimum performance requirements such as minimum percentage of the network in the structurally Strong category and/or maximum percentage of the network in the structurally Weak category. Historical performance can be used to determine if the state is achieving its desired goals or to identify deficiencies. Such results could be reported to the state legislature or to satisfy federal requirements such as the HPMS data submission to the Federal Highway Administration.

Identify Sections that are Candidates for Preservation Treatment

Identifying candidate sections for preservation treatment is an important step in effective pavement preservation. Wrongly identified sections result in wasted resources that could have been used for improvements elsewhere. Pavement preservation treatments extend the pavement life without adding structure to the pavement. As such, they should be applied on pavements that are already structurally sound (Strong or Fair) and not on structurally Weak pavements (i.e., use the right treatment at the right time for the right road). Therefore, road sections can be classified as adequate for pavement preservation based on the structural condition category as follows:

1. Structurally Strong sections: these sections are optimal for preservation treatments. These treatments will delay pavement deterioration and extend the pavement life.
2. Structurally Fair sections: these sections could still potentially be good candidates for pavement preservation depending on the type of treatment considered. Although preservation treatments on Fair sections will not last as long (or be as cost-effective) as they are on the structurally Strong sections, they can help maintain these sections in the Fair structural condition category for longer periods. Therefore, they can be valuable tools given the limited budgets for maintaining roadways.
3. Structurally Weak sections: these sections are very unlikely to be good candidates for preservation treatment. The sections are already structurally Weak, and an extensive number of distresses, if not already showing, will soon develop on the surface. Furthermore, preservation treatments will have very little effect on slowing down the development of distresses.

Determine Required Overlay Thickness

This approach is based on the AASHTO overlay thickness design. Given the SN_{eff}, and the SN_{req} that is based on the traffic data, and design life and reliability, the overlay thickness is determined as follows:

$$a_1 \times h_{ol} = SN_{req} - SN_{eff} \tag{18}$$

Where
h_{ol} = overlay thickness in inches
a_1 = layer coefficient (default 0.44 inch^{-1}) representing the thickness of the asphalt overlay (inches)
SN_{req} and SN_{eff} are as defined previously.

Not every treatment has to be an overlay. Therefore, the determined required overlay thickness can be used to determine the appropriate treatment category based on the pavement structural condition. An example is shown in Table 2.

Table 2. Recommended Treatment Categories Based on Calculated Overlay Thickness

Maintenance Category	Calculated Overlay Thickness (inches)
Do Nothing (DN)	$h_{ol} < 1$
Preventive Maintenance (PM)	$h_{ol} < 1$
Corrective Maintenance (CM)	$1 \leq h_{ol} < 3$
Restorative Maintenance (RM)	$3 \leq h_{ol} < 6$
Rehabilitation / Reconstruction (RC)	$h_{ol} \geq 6$

Modify Treatments Selected Based on the Surface Condition

Most highway agencies have implemented treatment selection procedures (decision trees) based on collected surface condition. Therefore, it could be beneficial to implement an approach that considers the recommendation based on the surface condition and then further improves the recommendation based on structural condition. This can be implemented in a two-step approach shown in Figure 5. The presented approach is based on the one currently used by the Virginia Department of Transportation on its interstate roads, with the structural condition obtained from FWD testing. The advantages of a two-step procedure as opposed to a one-step procedure (e.g., the procedure based on overlay thickness presented in the previous section) is that it incorporates the knowledge accumulated from the years of performing treatment selection based on surface condition. The structural condition can therefore be used to further improve treatment selection. Table 3 and Table 4 show two possible ways the treatment category based on the surface condition can be modified based on the structural condition. In Table 3, the modification is simple: starting from the treatment category obtained from the surface condition, modify the treatment category to the next heavier treatment if the structural condition is Weak (thresholds determined by one of the methods discussed in Chapter 4), modify the treatment category to the next lighter treatment if the structural condition is Strong, and keep the same treatment category if the structural condition is Fair. While this approach is simple, it has drawbacks. For example, given a pavement surface that looks relatively “new,” the initial decision would be to do nothing (DN). If the structural condition is Weak, DN is modified to preventive maintenance (PM) in Table 3. However, PM is not effective on sections that are already structurally Weak. Therefore, a more sensible approach would be to keep the decision as DN and allow that surface condition to further deteriorate and, in the future, schedule a treatment category that addresses both the surface condition and the structural condition. Similarly, if the structural condition is Strong and the selected treatment category based on the surface condition is PM, then it might be better and keep the selected treatment category PM, as this will further extend the structural condition of the pavement. These two modifications to Table 3 are implemented in Table 4. Of course, there are other possible ways of modifying the treatment categories based on the surface condition that an agency can use.

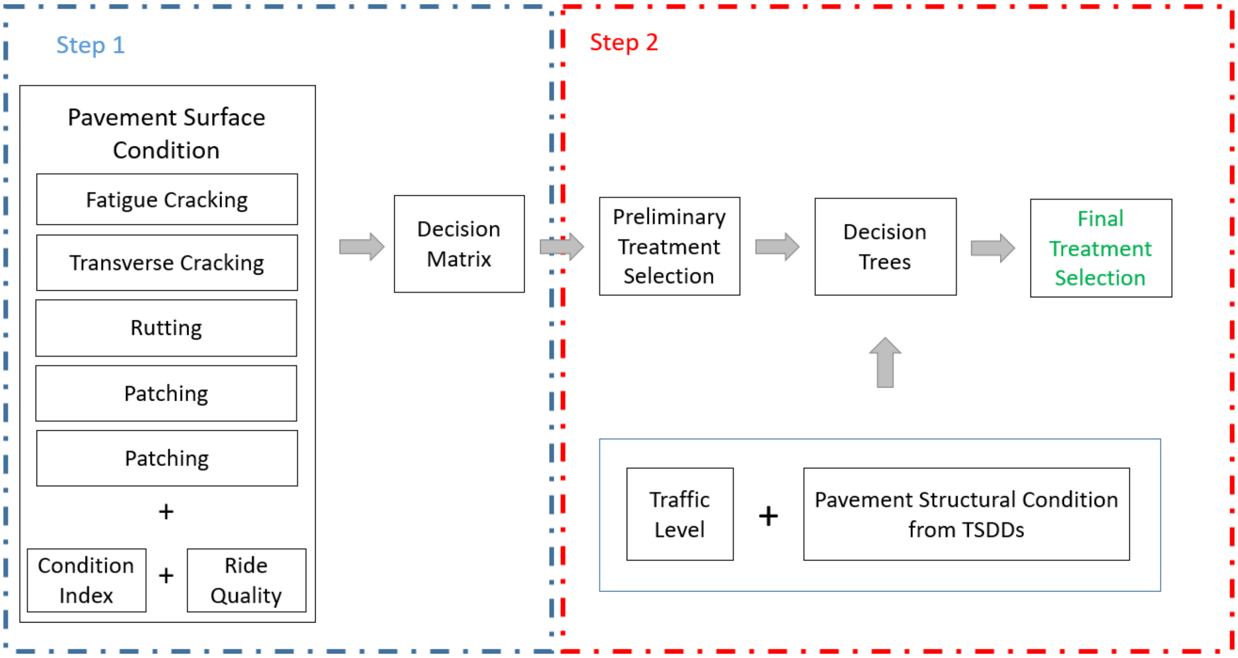

Figure 5. Two-step approach for incorporating the pavement structural condition into the current pavement management approach.

Table 3. Modified Treatment Category Based on Structural Condition – A

Initial treatment category based on surface condition	**Modified treatment category with structural condition category**		
	Strong	**Fair**	**Weak**
DN	DN	DN	**PM**
PM	**DN**	PM	CM
CM	PM	CM	RM
RM	CM	RM	RC
RC	RM	RC	RC

Table 4. Modified Treatment Category Based on Structural Condition – B

Initial treatment category based on surface condition	**Modified treatment category with structural condition category**		
	Strong	**Fair**	**Weak**
DN	DN	DN	DN
PM	PM	PM	**CM**
CM	**PM**	CM	**RM**
RM	**CM**	RM	**RC**
RC	**RM**	RC	RC

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