General Procedure for Pavement Maintenance/Rehabilitation Decisions Based on Structural and Functional Indices

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Abstract. Due to traffic loading and environmental conditions, pavements deteriorate over time. Other factors that may affect pavement performance are material properties and construction practices. However, it is important for road users to have the road network at a certain acceptable level. Typically, pavement functional indices, such as Pavement Condition Index (PCI), have been conspicuously utilized to determine which type of pavement maintenance/rehabilitation (M/R) should be applied for a specific pavement of a certain condition. Many researchers concluded that pavement surface condition, in some cases, does not reflect the condition of the underlying layers. Others argued that the treatment decisions based on the functional indices are sometimes overestimated or underestimated. This has galvanized many researchers to consider other indices, among of them are structural indices such as Structural Condition Index (SCI). Many studies recapped that the structural indices lead to more effective M/R decisions. Thus the current research aims to propose a more practical procedure for selecting the most appropriate M/R decision based not only on the functional indices as many highway agencies do but also on the existing structural condition of the degenerated pavement. To develop such procedure, data from 8 Long Term Pavement Performance pavement test sections were evaluated functionally and structurally and the decision was taken based on both functional and structural conditions. The proposed procedure is found to yield reasonable M/R decisions as compared to the use of either one of the indices.

Keywords: Structural condition index · Pavement condition index · M/R decisions · PMS · Overlay design · Maintenance decision tree

1 Introduction

In a Pavement Management System (PMS), flexible pavements can be evaluated functionally or structurally. The functional condition represents the ability of the pavement to carry the future loading at acceptable level of serviceability [1]. The structural condition can be defined as the capability of the pavement to carry the traffic

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loading over its design period [1]. Pavement distresses and ride quality have been used as the primary indicators for pavement preservation and timing [2]. The most eminent functional indices are Pavement Condition Index (PCI), International Roughness Index (IRI) and Pavement Condition Rating (PCR). These indices assess the current pavement condition contingent on the observable distresses on the pavement surface abjuring the condition of the sublayers. Functional condition is very essential, as it is related to the user's comfort and safety [3]. Nonetheless, these indicators cannot reflect the actual load carrying capacity or the structural condition of the pavement as the comparable structural indicators do [4]. Hence, suggested treatments based on these indicators are often overestimated or under estimated [5]. Chowdhury et al. (2012) stated that, the maintenance activity based on the functional indices is not the optimal treatment [6]. Additionally, Zaghloul et al. (1998) concluded that the results obtained from the functional indices may be independent of the underlying structure [7]. Therefore, the pavement structural condition should be considered for an effective M/R decision [5]. Pavement condition keeps exacerbating, notwithstanding amounts of seal coats and thin overlays are applied by state highway agencies every year. This, in part, is a result of rejecting the structural condition of pavement layers and subgrade soil. Considering the pavement structural condition leads to efficacious treatment decisions [8]. Structural condition is a hidden indicator and is not important to the user [3]. It is not considered in maintenance decision. From engineering view, functional and structural conditions are equally substantial for any PMS. A pavement surface in a poor condition can be construed as in a poor structural condition, however in some cases; a poor surface condition does not mean a poor structural condition [5].

2 Trials to Correlate Structural and Functional Indices

Over the years, many researchers tried to correlate the structural indices with the functional ones. To exemplify, deflection data collected from a section of (I-81) Southbound, Virginia, was utilized to examine the correlation between structural condition of the pavement in terms of Structural Condition Index (SCI) and functional condition of the pavement in terms of Load Related Distress Rating (LDR). The study also tried to collate center deflection and LDR. SCI is the structural condition index and it will be defined in the next section and LDR is a function of the distresses exhibited in the wheel path as presented in Eq. (1) [9]:

$$LDR = \text{Deduct\_Alligator\_Crk} - \text{Deduct\_Rutting} - \text{Deduct\_Patching} \quad (1)$$

The results indicated that there is no correlation between structural and functional indices [10]. Flora (2009) tried to correlate the Falling Weight Deflectometer (FWD) deflections and functional indices namely IRI, PCR, or the rut depth. The results show that, at 95% confidence level, there is no statistical correlation between these indices [11]. A t-test was conducted between the PCI and Structural Health Index (SHI), which is a structural index developed for Louisiana Department of Transportation, to examine the relation between these two indices statistically. A significant difference was found between the indices represented by a P-value of 0.001. Also, a

Pearson correlation coefficient of 0.41 was found indicating a poor correlation between them [2]. It can be concluded from the previous studies that there are no obvious correlations between structural and functional indices. Based on the previous discussion, it is imperative to realize the importance of conflating both structural and functional indices to obtain a full evaluation for the pavement condition. Thus the main objective of this research is to find a more pragmatic way for an efficacious treatment or rehabilitation decision. That may be achieved by taking the decision based on both structural and functional indices simultaneously. This means, the functional indices can be used to provide an assessment for the current pavement surface condition, and the structural condition would help know the pavement load carrying capacity. In this study the PCI is used to evaluate the pavement condition functionally, and the SCI is considered for the pavement structural evaluation.

3 Structural Condition Index (SCI)

The SCI is defined as the ratio between the SN_{eff} and the required SN (SN_{req}) as presented in Eq. (2) [8].

$$SCI = \frac{SN_{eff}}{SN_{req}} \tag{2}$$

Where
SCI = structural condition index.
SN_{eff} = existing pavement structural number.
SN_{req} = required structural number.

As can be seen, SCI is a simple index and the interpretation of its meaning is straightforward. For SCI value equal to or more than one, the pavement would be intact. It may also be sufficient for the future required Equivalent Single Axel Loads (ESALs). In this case the pavement may only require a preservation maintenance activity (crack sealing or chip sealing). Conversely, the pavement requires a rehabilitation or reconstruction activity if the SCI value is lower than one. The pavement in this case is enfeebled and is not adequate for the estimated future traffic loads. Nam et al. (2016) reformed the decision of M/R based on SCI values as presented in Table 1 [12]. For the prediction of the SN_{eff}, there are many models available in the literature [13, 14]. Based on the comprehensive evaluation of the most known models using the Long Term Pavement Performance (LTPP) data, Abd El-raof et al., 2018b, reported that the calibrated Kavussi et al. model is recommended to calculate SN_{eff} [14]. Calibrated Kavussi et al. model is presented in Eq. (3):

$$SN_{eff} = K_1 * D_0^{K_2} * D_{90}^{K_3} \tag{3}$$

Where:
D_o = peak deflection at a standard 9000-Ib FWD load (microns).
D_{90} = deflection at radial distance of 90 cm from the center of loading plate (microns).
K_1, K_2, and K_3 = regression coefficients = 85.740, −0.770 and 0.310, respectively.

Table 1. Pavement treatment decision based on SCI value (Nam et al. 2016)

SCI *100	M/R decision	Treatment example
>90	Do nothing	—-
80–90	PM	Seal Coat Crack seal Thin Overlay (1″-2″)
65–80	LRhb	Seal Crack and place 1.5″ ACP Spot Repair and 1.5″ Overlay Seal Coat and 2″ to 3″ Overlay
50–65	MRhb	Mill ACP and 2″-4″ ACP Overlay Mill 5.5″ ACP and replace with 5.5″ Overlay
<50	HRhb	Remove Existing Pavement, 10″-12″ Lime Treat Subgrade, Place New Flexible Base, and 2″ ACP. Remove 5″ ACP and Place 8″ ACP

On the other hand, the SN_{req} can be estimated according to the expected ESALs accumulated during the desired design period using Eq. (4) [15].

Where PM = Preventative Maintenance, LRhb = Light Rehabilitation, MRhb = Moderate Rehabilitation, HRhb = Heavy Rehabilitation, and ACP = Asphalt Concrete Pavement

$$\log W_{18} = Z_R S_o + 9.36 \log(SN + 1) - 0.2 + \frac{\log[(\Delta PSI)/(4.2 - 1.5)]}{0.4 + 1094/(\mathrm{SN} + 1)^{5.19}} + 2.32 \log M_R - 8.07 \tag{4}$$

Where:

W_{18} = 18 Kips (80 KN) equivalent single axle load application number.

Z_R = a normal deviate for a given reliability (R).

S_o = overall standard deviation of traffic.

SN = required structural number (in.).

ΔPSI = loss in serviceability.

MR = subgrade resilient modulus (psi).

4 Pavement Condition Index (PCI)

Based on visual survey, pavement surface condition can be quantified using the traditional PCI. PCI is a numerical value (ranges from 0 to 100) which rates the surface condition of the pavement. The value of 100 represents the best condition, while the worst condition is represented by a value of 0 [16]. It is a tool for rating the pavement and may also be used for the maintenance/rehabilitation alternatives. Continuous observation of the pavement condition and determination of the PCI value can be used to establish pavement deterioration curves which permit the early identification of maintenance and rehabilitation needs. Through PCI, the current design and maintenance procedure can be verified and improved [16]. The PCI value is decreased by a deduct value which depends on the severity and extent of the surface distresses. Severity of each distress can either be Low (L), Medium (M), or High (H). This classification is determined according to the distress level of deterioration. Based on the PCI value, the pavement surface condition can be rated as Good to Failed. In addition, maintenance/rehabilitation decision can be taken according to Table 2.

Table 2. M/R strategy according to PCI value [17]

PCI	Rating	Strategy
85–100	Good	Preventative maintenance
70–85	Satisfactory	Minor rehabilitation
55–70	Fair	Minor rehabilitation
40–55	Poor	Major rehabilitation
25–40	Very poor	Major rehabilitation
10–25	Serious	Reconstruction
0–10	Failed	Reconstruction

5 Data Collection

A total of 8 pavement sections from the Specific Pavement Study (SPS-1) of the Long Term Pavement Program (LTPP) program were used in this research. These sections were selected such that they cover all four climatic regions in the U.S. as well as different subgrade types, traffic levels, and pavement structure layer thicknesses. The climatic regions in the U.S. are classified into wet/freeze, dry/freeze, wet/non freeze, and dry/non freeze and are referred to as WF, DF, WNF, and DNF, respectively [18]. Table 3 presents the structural system, climatic region, subgrade type, and test dates of each section. In addition, the number of FWD data measurements is presented.

Table 3. Main properties of SPS-1 section used for SCI and PCI calculations

Section ID	Climatic region	Layer yhickness, in. (mm)			Subgrade type	Test date
		AC	GB	GS		
01-0101	WNF	7.40 (188)	7.90 (201)	–	A-7-5	4/28/2005
01-0102	WNF	4.20 (107)	12.00 (305)	–	A-7-6	5/28/2002
04-0114	DNF	6.80 (173)	12.00 (305)	–	A-2-4	4/2/2002
10-0101	WF	7.00 (178)	8.10 (206)	39.00 (990)	A-2-4	10/4/2005
10-0102	WF	4.30 (109)	11.80 (300)	39.00 (990)	A-2-4	8/13/1996
19-0101	DF	7.70 (196)	8.00 (203)	25.00 (635)	A-6	2/16/2001
30-0113	DNF	5.80 (147)	8.40 (213)	–	A-1-b	7/16/2001
31-0114	DF	6.60 (168)	12.00 (305)	24.00 (610)	A-7-6	7/10/2000

AC = Asphalt Concrete Layer, GB = Granular Base Layer, GS = Granular Sub-base Layer, DF = Dry, Freeze, DNF = Dry, Non Freeze, WF = Wet, Freeze, and WNF = Wet, Non Freeze.

6 PCI and SCI Calculations

The PCI values were calculated according to the ASTM-D6433 procedure [16]. The PCI values are decreased by the deduct values obtained based on the distress type and its severity. At each test date, the SCI was also calculated for the same sections. SN_{eff} value was calculated using Calibrated Kavussi et al. model as can be shown in Eq. (3), while SN_{req} was calculated using the AASHTO 1993 nomograph. The SCI values for some sections are presented in Fig. 1. In addition, Table 4 gives a recapitulation of SCI and PCI values for the eight used sections.

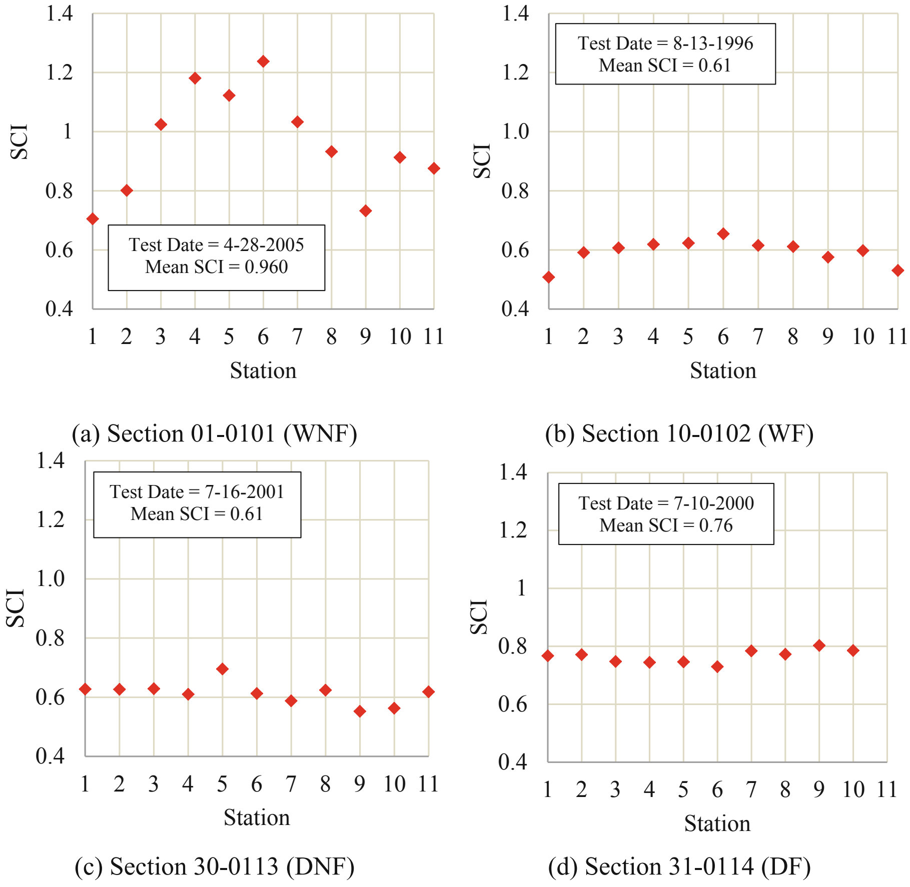

Fig. 1. SCI variations along the selected sections

7 Discussion of Results

It can be seen that the PCI values for 01-0101, 30-0113, and 31-0114 LTPP sections have similar functional condition. However, these sections have disparate SCI values which indicate different structural capacity for future traffic loading. In other words, using the same M/R decision based on the PCI value for these sections would not be fallacious. Thus, the structural condition should be taken into account for more effective maintenance decisions. The same condition exists for Section 01-0102, 04-0114, and 19-0101 with negligible difference in the functional condition as indicated by the PCI values and a significant difference in the structural condition indicated by the SCI values. Moreover, Section 10-0102 and 31-0113 have the same structural condition but they are functionally different. In addition, Section 01-0101 and 04-0114 have the same structural capacity with significantly different PCI values. These results indicate that; the functional indices are independent of the structural condition which confirms the results of other studies such as Zaghloul et al. (1998) [7]. The results also reveal that a high functional performance does not mean a sound structure as shown in the case of Section 10-0102. These results imply that the SCI can discriminate between strong and weak pavements. Therefore, it can be used as a screening tool for network level evaluation. Its simple interpretation and meaning makes it a robust candidate for network level evaluation.

Table 4. Table PCI and SCI values for the selected sections

Section ID	Test date	PCI (%)	SCI
01-0101	4/28/2005	63.00	0.96
01-0102	5/28/2002	31.17	0.58
04-0114	4/2/2002	30.03	1.05
10-0101	10/4/2005	19.08	0.77
10-0102	8/13/1996	85	0.61
19-0101	21/6/2001	38.57	0.80
30-0113	7/16/2001	64.09	0.61
31-0114	7/10/2000	64.46	0.76

8 Selecting the M/R Decision

Based on the PCI and SCI values summarized in Table 4, the appropriate M/R decision can be taken. The threshold values illustrated in Tables 1 and 2 can be used for this purpose. Additionally, the flow chart presented in Fig. 2 is proposed to simplify the decision making. For LTPP Section 01-0101, the SCI value of 0.960 requires "Do Nothing" as it is structurally adequate for the future traffic loading. This means that, the section is able to serve for another design period without any treatment. Conversely, the PCI value of 63% indicates that the pavement condition is fair as presented in Table 2. In other words, light to moderate rehabilitation is recommended based on the PCI value. Thus, the "Do Nothing" treatment based on SCI value is insufficient for the future performance of the section and the user satisfaction. Existence of surface cracks may permit the water to get into the sublayers causing a faster rate of deterioration. In this case preventative treatment such as (Seal Coat or Crack Sealing) will be an effective decision. This proves that, for effective treatment alternative, structural and functional indices should be considered together. Therefore, in Fig. 2 a preventative maintenance is required for a longer future performance than the "Do Nothing" activity. Additionally, a thin overlay can be applied after crack sealing to obtain a smooth surface with low level of roughness and high degree of friction in order to improve the functional performance of the pavement.

For LTPP Section 10-0102, the PCI value of 85% indicates that the pavement surface condition is good. This means a preventative maintenance is required for this section as indicated in Table 2. Conversely, the SCI value of 0.61 implies that this section cannot serve for the desired design period. As indicated in Fig. 2, if a preventative activity is applied without considering the structural condition, this section will significantly deteriorate before the end of the design period. Based on Table 1, this section requires an "MRhb" activity such as "Mill Existing ACP and applying 2″-4″ (5 to 10 cm) ACP overlay". The PCI value indicates that milling the surface layer is uneconomic idea. Additionally, overlaying with 2″-4″ (5 to 10 cm) ACP may be insufficient to carry out the future EASLs. For more effective alternative, both structural and the functional conditions should be considered. Examining the distresses in this section which has a PCI value of 85% indicates little amount of low severity fatigue cracks (9.8 m^2) as reported in LTPP. Instead of milling the whole surface layer area which costs time and money for removing the aged layer and placing the new one, patching the damaged area offers an economic alternative. Patching is the most popular technique of repairing localized areas with intensive cracks. After patching, the required thickness of overlay can be placed without any fear of reflective cracks. The thickness of the overlay can be determined such that the SN_{eff} value becomes $\geq$ 90% from SN_{req}. Equation (5) can be used to estimate the required overlay thickness.

$$d = \frac{SN_{req} - SN_{eff}}{0.44(1 - c)} \tag{5}$$

Where: SN_{eff} = existing structural number. SN_{req} = required structural numberC = coefficient presents the condition of the existing pavement (For flexible pavements C can be assumed (0.5–0.7).

For the remaining sections, the PCI values (19.08 to 64.46) indicate that, pavement surface conditions ranged from serious to fair. On the other hand, SCI values ranged from 0.58 to 1.05 indicates a good structural condition. Selecting the M/R activity based on the low PCI value and ignoring structural conditions leads to an uneconomic decision. For example, Section 10-0101 has a PCI value of 19.08 which indicates a serious pavement condition. In this case the pavement requires a reconstruction strategy to be applied. An SCI value of 0.77 indicate that the pavement is strong and requires a light rehabilitain to be applied. Much time and money will be lost if the reconstruction activity is applied. On the other side, if a light rehabilitation, based on SCI value, is applied reflective cracks may appear after short time from applying it. This discussion

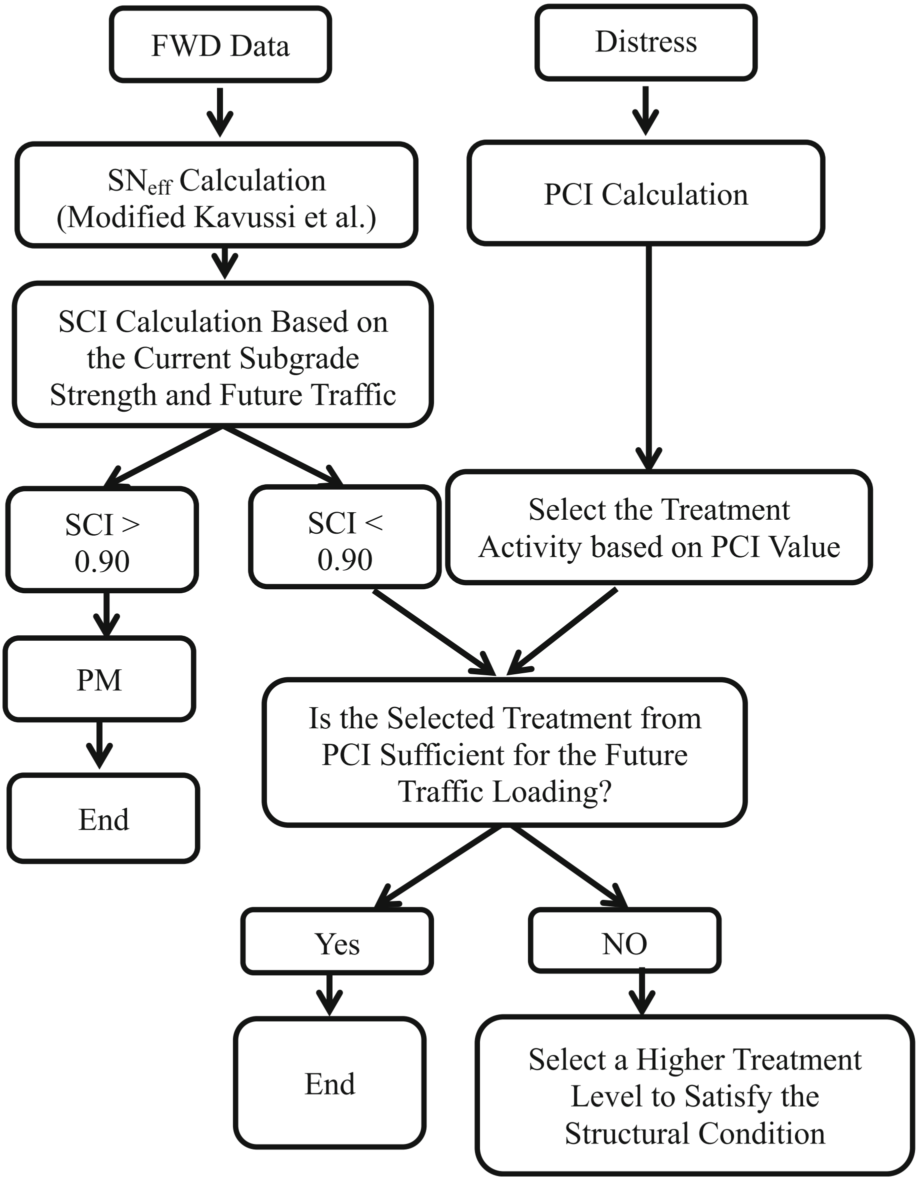

Fig. 2. Flow chart used to select the appropriate M/R based on PCI and SCI

reveals that the structural and functional indicies should be combined for effective M/R decisions. Milling the damaged surface and applying a well designed and constructed overlay layer represnt a robsut alternative in these cases. However, before milling, the existing pavement should be well evaluated. The evaluation of the existing pavement can be conducted based on the flow chart presented in Fig. 3. As can be seen in the figure, FWD testing is required for investigation. The second step is to evaluate the

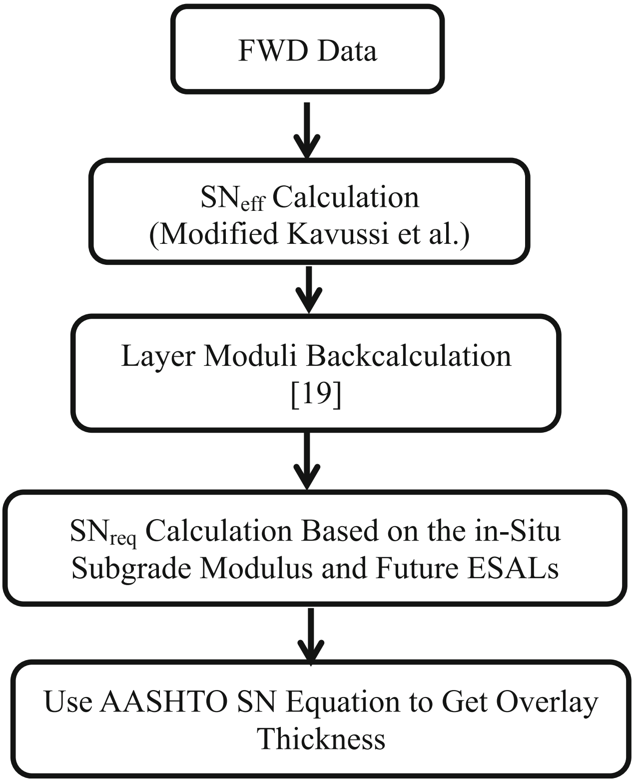

Fig. 3. Suggested procedure for selecting the best M/R decision in case of low PCI and high SCI

existing pavements in terms of SN_{eff} using modified Kavussi et al. model [14]. More investigation is required in terms of AC, base, and subgrade in situ resilient modulus. AC and base layer modulus can be estimated by the recommended procedure by Abd El-raof et al. (2018c) [19], while subgrade resilient modulus can be calculated using Eq. (5). Beside subgrade resilient modulus, future ESALs can be used to calculate $SN_{req.}$ Now the pavement can be milled. With the in situ base modulus, base layer coefficient (a_2) can be calculated and multiplied by the insitu base layer thickness to obtain the contribution of base layer in SN_{req}. AASHTO SN equation can be used to get the accurate overlay thickness after knowing the properties of the mix used in the overlay layer.

$$E_{SG} = -346 + 0.00676 * \left(\frac{2P}{D_{36} + D_{48}} \right) \quad (5)$$

Where:

P = applied load (Ibs.). D_{36} and D_{48} = measured deflections at 36 and 48 in. (90 and 122 cm) from the load plate (in.).

9 Summary and Conclusion

Selecting the most appropriate M/R strategy is considered one of the major outcomes of an effective PMS system. The treatment should be selected on the basis of the current condition and the future performance. The existing pavement condition is evaluated by PCI to reflect the actual condition of the surface. On the other hand, SCI is used to reflect the future performance of the pavement under the expected traffic loading. The results indicated that, the functional condition is independent of the structural condition. Additionally, Selecting M/R activity using the structural and functional indices together results in more effective decisions. This tentative study shows the powerful outcome of combining both PCI and SCI in making a credible maintenance/rehabilitation decision.

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