Use of Structural Condition Index for Pavement Structural Evaluation Tool

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Abstract

In this study, an effort was made to evaluate pavement condition using the pavement structural condition index (SCI), which is based on falling weigh deflectometer (FWD) deflection basin and structural numbers that incorporated various levels of traffic and subgrade resilient modulus. Extensive field validations were conducted to assess the effectiveness of SCI along with comparison of pavement distress and condition score restored in the Pavement Management Information System (PMIS). The analysis results revealed that the SCI appears to realistically capture the existing pavement condition compared to the pavement scores and field survey results. Based on this finding, probabilistic and deterministic models were developed to estimate SCI when FWD data is not available. These models are deemed most useful for network-level analysis purposes to aid establish pavement maintenance and rehabilitation plans.

Key words: Falling weigh deflectometer deflection basin, Pavement structural condition index, Pavement management information system, Probabilistic and deterministic models, Subgrade resilient modulus

1. Introduction

There are numerous ways to evaluate pavement condition. Non-destructive methods have widely been used to detect pavement structural deficiency and evaluate structural adequacy. Visual survey has been basically regarded as reference with regard to pavement condition assessment, which is mostly adopted in various transportation agencies all over the world. Over the years, many highway agencies have applied extensive maintenance treatments to highway to preserve or improve the surface condition. However, it is not difficult to confront such deterioration in a short period because of the structural deformation of pavement layers and the subgrade. To address this issue, Zhang et al. (2003) developed a new methodology called the Structural Condition Index (SCI), using Falling Weigh Deflectometer (FWD) data. The SCI is the ratio of the existing Structural Number ($SN_{eff}$) determined from both the FWD measurements and the total pavement thickness, which is proposed by American Association of State Highway and Transportation (AASHTO) in 1986, to the required SN ($SN_{req}$) based on the estimated 20-year Equivalent Single Axle Loads (ESALs) for the route, and the subgrade resilient modulus proposed by the AASHTO in 1993 as shown in Eq. (1).

$$SCI = \frac{SN_{eff}}{SN_{req}}$$  (1)

As indicated, if the SCI value becomes smaller, the exist-
ing pavement condition is deemed problematic that calls for rehabilitation in a near future.

In this study, the authors employed the SCI concept to evaluate pavement structural condition for further verification and along with timely FWD data availability during this study.

2. SCI Algorithm

The following procedures can be used to estimate SCI.

1) Step 1: Normalize FWD measured deflections to 9 kips (40 kN) and standard load & temperature. In this study the algorithm to accommodate temperature correction was added to the original procedure that only accounted for load effect. Chen et al. (2000) reported that only the \( W_1 \) (closest to the loading plate) and \( W_2 \) FWD deflections are significantly influenced by pavement temperature. The study developed an equation to take into account the temperature effect on the FWD maximum deflection, as shown below.

\[
W_{Tw}^{1} = W_{Tw} \left( \frac{1.8023 \times 10^{-0.0098t}}{0.8631} \right) T_{w}^{0.8316} T_{c}^{-0.8419} \tag{2}
\]

where \( W_{Tw} \) is \( W_1 \) deflection adjusted to temperature \( T_w \) (mm); \( t \) is thickness of the asphalt concrete (AC) layer (mm); \( T_w \) is temperature to which the \( W_1 \) deflection is adjusted (°C); and \( T_c \) is mid-depth temperature at the time of FWD data collection (°C). In this paper, \( T_w \) was chosen 25°C, as a reference temperature. With regard to normalizing \( W_2 \) deflection, a simple interpolation was applied using normalized \( W_1 \) and \( W_2 \) un-normalized deflections.

2) Step 2: Determine the deflection at an offset of 1.5 times total pavement thickness (\( H_p \)) call it \( W_{1,5H_p} \). Where the total pavement thickness that is a sum of thicknesses of layers above subgrade in mm. Eq. (3) is used to compute \( W_{1,5H_p} \):

\[
D_{X} = \frac{[(R_{X} R_{B})^{*}(R_{X} R_{C})]/(R_{B} R_{C})^{*}(R_{A} R_{C})]*D_{A}}{[(R_{X} R_{B})]/(R_{B})^{*}(R_{B} R_{C})]*D_{B}} + [(R_{X} R_{B})]/(R_{B} R_{C})]*D_{C}
\tag{3}
\]

where \( D_x \) is deflection at offset of \( R_x \), \( D_i \) is deflection at sensor \( i \), \( R_i \) is offset of sensor \( i \), \( i \) is \( A,B,C \) the three closet sensors to point \( X \), and \( X \) is point for which deflection is determined.

3) Step 3: Determine the structural index of a pavement (SIP) in microns using Eq. (4).

\[
SIP = W_1 - W_{1.5H_p} \tag{4}
\]

4) Step 4: Determine the \( S_{Neq} \) in inches via Eq. (5).

\[
S_{Neq} = k_1 \times SIP^{k_2} \times H_p^{k_3} \tag{5}
\]

where the \( k \) coefficients are presented in Table 1 (Zhang et al., 2003).

5) Step 5: Determine the estimated subgrade resilient modulus (\( M_r \)) in psi using Eq. (6). Where \( P \) is FWD load.

\[
M_r = 0.192*P/W_{Tw}^{*72} \tag{6}
\]

6) Determine the \( S_{Neq} \) in inches using Table 2.

7) Step 7: Determine the SCI using Eq. (1).

3. Field Validation

SCI was computed using available data for eight roadway corridors in the Fort Worth District and 25 corridors in the Bryan District in Texas. For the sections, the data on FWD deflections, surface type, and total pavement thickness were obtained from FWD measurements and ground penetrating radar (GPR) surveys that were conducted in the summer of 2010. 20-yearer accumulated ESALs were obtained from the PMIS database for each route, which is maintained by the Texas Department of Transportation (TxDOT).

For brevity, the detailed data for FM 52 and FM 2257 only are presented and discussed here. These corridors represent two different cases that provide insights into the patterns and possible associations between FWD data and PMIS scores. PMIS takes the pavement evaluation data and computes five scores which describe various aspects of pavement condition. These scores use utility factors to adjust the ratings and data into a uniform scale for comparison purpose. These scores are: distress score, a measure of visible surface deterioration (pavement distress), ride score (a measure of pavement roughness), condition score (a measure of overall condition in terms of distress and ride quality). These scores for asphalt concrete pavement sections are computed as below (Texas DOT, 2010).

\[
DS = 100 \times (U_{SRut}^{*} U_{DRut}^{*} U_{Patch}^{*} U_{Fail}^{*} U_{Blk}^{*} U_{Alg}^{*} U_{Lng}^{*} U_{Tra}) \tag{7}
\]

where \( DS \)=distress score, \( U \)=utility value, \( SRut \)=shallow rut-
ting, DRut=deep rutting, Patch=patching, Fail=failures, Blk=block cracking, Alg=alligator cracking, Lng=longitudinal cracking, and Trn=transverse cracking.

The ride scores are measured automatically and reported on a scale from 0 to 5, which is the user perception correlated to the roughness of the highway. To arrive at a final PMIS condition score (CS), the distress utility and ride utility scores are combined as shown below.

\[ CS = 100 \times U_{DS} \times U_{RS} \]

PMIS database is being upgraded annually therefore the pavement rating scores represent one year before pavement condition. That is, the pavement rating of 2010 will be restored in 2011 PMIS database. The first case (FM 2257) shows fairly uniform deflection measurements; while the second case (FM 52) shows high variability in deflection measurements along the tested segment.

3.1 FM 2257 Evaluation

This 4-mile (6.4 km) segment of FM 2257 is located in Parker County. The GPR survey and FWD tests were conducted in August 2010. As illustrated in Fig. 1, several patched areas existed near Reference Marker (RM) 544. This is consistent with the 2011 condition and distress scores (obtained from PMIS). According to the GPR data, the total pavement thickness of this roadway segment ranged from 177.8 mm to 279.4 mm, as shown in Fig. 2. It is worthwhile noting that taking into account the variation of total pavement thickness along the segment based on GPR survey should be advantageous to improve the accuracy in estimation of SCIs rather than solely relying on average thickness that can be obtained from the plans or limited coring and boring. To verify this, a sensitivity analysis was conducted as shown in Fig. 3 by varying the total pavement thickness from 15 to 56 cm. As indicated, the SCIs almost linearly varied due to the change of total pavement thickness. The results of this sensitivity analysis demonstrate the importance of using accurate total pavement thickness in SCI calculations.

Normalizing FWD deflections with respect to reference load and pavement temperature generally yields higher SCI values than those normalized by 40 kN of standard load only as shown in Fig. 4. In the plot, the SCI computed values were multiplied by 100 to compare with PMIS scores. The measured pavement temperature was ranged from 35 to
40°C during FWD data collection. It was shown that the PMIS scores and SCI follow a similar pattern. This roadway segment is an example of cases where deflection measurements are uniform, and consequently SCI and PMIS scores are consistent (i.e., follow a similar pattern). In these cases, it appears reasonable to use SCI in the maintenance and rehabilitation (M&R) project prioritization process.

3.2 FM 52 Evaluation

This segment of FM 52 (RM 506-0.1-512+1.75) is located in Palo Pinto County. The GPR survey and FWD tests were conducted in August 2010. As illustrated in Fig. 5, the section exhibited no surface distress, which is consistent with 2011 PMIS scores that yield 100 for the entire segment. The section was treated by full depth reclamation (FDR) in early 2010. According to the GPR data, the total pavement thickness of this roadway segment ranged from 20.8 to 43.2 cm.

While normalizing deflections based on temperature and load reduced measurement variability, extreme SCI values remain present (see Fig. 6). In this case, SCI computed for individual FWD tests (e.g., taken every 0.1 mile (160 m)) may not agree with PMIS distress and condition scores (which typically represent the pavement condition over 0.5-mile (800 m) long sections). These discrepancies between SCI and condition and distress scores are mainly due to the data sampling interval differences. However this discrepancy also infers that SCI is able to capture structural inadequacy of pavement underlying layers even though that may not be appear in pavement surface. From the practical view, in spite of having narrower data sampling interval will be challengeable, it will be appropriate to have such intervals particularly in pavement segment where tends to exhibit frequent pavement deteriorations associated with extreme traffic and environmental factors.

4. Prediction of SCI Based on Changes in Distress Score

SCI can potentially be considered by the transportation agencies when developing their M&R plans, as a measure of the pavement’s structural condition. However, in many cases the FWD data needed to compute SCI is not available. The models developed in this study and discussed herein provided the agencies with a tool to predict SCI as a function of distress score value and annual drop. The rational of these models is that a significant drop in distress score can be associated with inadequate structural adequacy, which is estimated in terms of SCI. This concept is illustrated in Fig. 7. If $DS_0$ is the value of DS (Distress Score) in the year prior to year of the FWD deflection testing (i.e., the SCI year) and $DS_1$ is the value of DS in the same year of FWD testing; the drop in DS ($\Delta DS$) is the difference between $DS_0$ and $DS_1$ ($DS_0-DS_1$).

The FWD tests were delineated for each PMIS section. To ensure adequate representation of the entire PMIS section (typically 0.5-mi long), only PMIS sections that have at least five FWD tests per section are used in this analysis. Initial comparisons between SCI and PMIS scores (both score value and annual drop) showed that sections with SCI...
<50 have the least agreement between the PMIS scores and SCI. There were 29 sections in this category, which were excluded from any further analysis. Ultimately, 123 PMIS sections (out of the initial 152 sections) were used in developing deterministic and probabilistic models for predicting SCI as a function of distress score value and annual drop. Note that the SCI plotted are based on temperature and load normalization of FWD deflection data.

4.1 Deterministic Model for Predicting SCI

Based on the limited data available in this study, a reasonable trend exists between the calculated SCI and drop in DS when the current DS is greater than 70 (see Fig. 8); however, no such trend could be found when the current DS is less than 70 (see Fig. 9). For the purpose of identifying pavement sections that need M&R work, the second case is irrelevant since the low DS is likely to identify these sections for possible M&R work, regardless of the SCI value.

The following best fit model represent the relationship between SCI and drop in DS when current DS is greater than 70:

\[
SCI_{AVE} = \frac{100}{1 + \alpha \Delta DS} \beta
\]

(9)

Where, \( \alpha \) and \( \beta \) are regression coefficients. The fitted coefficients are 0.0189 and 0.9333 with standard errors of the estimate (SEE) of 10.8. The value of SEE is deemed to be acceptable based on the current TxDOT maintenance and rehabilitation (M&R) practice shown in Table 3.

For example, if the value of SCI is determined 75, engineers can have maintenance and rehabilitation options either preventive maintenance or light rehabilitation contingent on local availability with respect to budget and material allocations.

4.2 Probabilistic Model for Predicting SCI

To provide agencies with an additional tool for estimating SCI when FWD data are not available, the authors employed a probabilistic approach to detect structurally-weak pavements based on current DS and DS. Peddibhotla et al. (2011) suggested that an SCI greater than 80 indicates that the pavement does not need any type of rehabilitation (which indicates that the pavement is structurally adequate). A probabilistic model that allows for predicting the probability that SCI is less than 80 based on current DS (i.e., \( DS_1 \)) and DS was developed herein. This model is based on the conditional probability mass function, which is defined as follows:

\[
P_{X,Y,Z}(x|y,z) = \frac{P_{X,Y,Z}(x,y,z)}{\sum_{x} P_{X,Y,Z}(x,y,z)}\frac{P_{X,Y,Z}(x,y,z)}{P_{Y,Z}(y,z)}
\]

Where, \( x, y, \) and \( z \) are three discrete random variables; \( x \) is the conditional probability of \( x \), given \( y \) and \( z \); and \( x, y, \) and \( z \) represent SCI, DS, and \( DS_1 \) conditions, respectively (e.g., SCI<90, DS>10, and DS=70).

The above model was employed to compute the probability of having SCI less than 80 for various ranges of \( DS_1 \) and DS (see Table 4). This probability can be used as an indicator of structural inadequacy when FWD measurements are not available (and consequently SCI cannot be computed directly). For example, if the current DS is greater than 70 and the drop in DS since last year was greater than 10 points, there would be a 68 percent chance that the pave-

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**Table 3. SCI Thresholds for M&R (Peddibhotla et al., 2011)**

<table>
<thead>
<tr>
<th>SCI Scores (SCI*100)</th>
<th>M&amp;R Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-100</td>
<td>Do Nothing</td>
</tr>
<tr>
<td>80-89</td>
<td>Preventive Maintenance</td>
</tr>
<tr>
<td>65-79</td>
<td>Light Rehabilitate</td>
</tr>
<tr>
<td>50-64</td>
<td>Medium Rehabilitate</td>
</tr>
<tr>
<td>0-49</td>
<td>Heavy Rehabilitate</td>
</tr>
</tbody>
</table>
ment is having structural problems (i.e., its SCI is less than 80). While this approach appears promising, it is limited to the data that were available in this study and thus requires further validation.

5. Conclusions

An effort was made to employ the concept of SCI to evaluate pavement condition based on field validation along with comparison with PMIS database. The following findings and conclusions were made:

1) Normalizing FWD data with respect to reference FWD load and pavement temperature appears to improve the accuracy of SCI.

2) Taking into account the variation of total pavement thickness using GPR survey along the evaluated segment is deemed advantageous in assessment of SCI. A parallel sensitivity analysis exhibited the sensitivity of SCI to the total pavement thickness.

3) Since the SCI is computed using FWD deflection basins, an ideal FWD testing interval will help improve the accuracy of the pavement structural condition assessment at the network level. From this study, a data collection spacing of 160 m (0.1 mile) was considered appropriate to establish pavement M&R plan particularly in pavement segments where tend to exhibit frequent pavement deteriorations associated with extreme traffic and environmental factors.

4) Preliminary deterministic and probabilistic models were established from this study. It is regarded as useful approach in assessment of SCIs when FWD data are not readily available. Further validations need to be conducted with additional data in the near future.

References


Table 4. Conditional probability of SCI<80 based on DS1 and DS

<table>
<thead>
<tr>
<th>Category</th>
<th>DS1&lt;70</th>
<th>DS1≥70</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆DS&lt;5</td>
<td>55%</td>
<td>32%</td>
</tr>
<tr>
<td>5≤∆DS≤10</td>
<td>67%</td>
<td>40%</td>
</tr>
<tr>
<td>∆DS&gt;10</td>
<td>82%</td>
<td>68%</td>
</tr>
</tbody>
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