INCORPORATING TRAFFIC SPEED PAVEMENT DEFLECTION DATA IN PAVEMENT MANAGEMENT DECISION MAKING FOR FLEXIBLE PAVEMENTS

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ABSTRACT
Systematic pavement condition evaluation and development of an optimized set of pavement treatment strategies are two key tasks in the pavement management process that assists in making informed decisions on future construction actions. Current State Highway Agency’s pavement management systems are primarily based on surface condition data, and surface cracking is mainly used as an indicator of the pavement structural condition. However, with effective pavement preservation activities that intervene early to preserve and extend the life of pavements and increasingly thicker long-life pavements, the surface cracks can no longer be a reliable indicator of structural condition of the pavement structure. This study envisions the use of data from Traffic Speed Deflection Devices (TSDD) in network level structural assessment and optimizing the pavement treatment strategies for flexible pavements within a modern pavement management framework. The methodology used the tensile strain at the bottom of the asphalt layer predicted from TSDD measurements to evaluate structural deterioration well before the occurrence of surface cracks, enabling more optimum treatment intervention. Mechanistic analyses were used to predict treatment benefits as a function of time and pavement condition at the time of application. The methodology allows the pavement engineer to identify an optimized series of treatment types and their timing over an analysis horizon that minimizes the life cycle cost while maintaining an above acceptable level of service. Finally the study illustrates the effectiveness of Remaining Service Interval (RSI) concept for consistent reporting of future construction needs based on optimum time remaining until a defined treatment type.

INTRODUCTION
The Moving Ahead for Progress in the 21st Century Act (MAP-21) defines asset management as a “strategic and systematic process of operating, maintaining, and improving physical assets, with a focus on both engineering and economic analysis based upon quality information, to identify a structured sequence of maintenance, preservation, repair, rehabilitation, and replacement actions that will achieve and sustain a desired state of good repair over the lifecycle of the assets at minimum practicable cost” (1). Applied to Pavement Management Systems (PMS), the above definition can be interpreted as 1) quality information through systematic pavement condition evaluation and 2) use of that information to identify a structured sequence of pavement treatment actions that maintains the pavement above acceptable level of service (LOS) at the lowest cost over the pavement lifecycle. This study demonstrates that the traffic speed deflection devices (TSDD) when combined with state-of-the-practice condition assessment and mechanistic analysis can address these two functions of the PMS. The proposed approach is discussed in the following three sections.

• Evaluate and incorporate structural and functional pavement condition in network analysis.
• Integrate mechanistic and life cycle cost (LCC) analyses in identifying the optimized treatment sequence and its timing.
• Utilize Remaining Service Interval (RSI) concept in reporting the optimum time remaining until a defined construction treatment type.

COMBINED MONITORING OF STRUCTURE AND FUNCTIONAL CONDITION IN NETWORK ANALYSIS
Network pavement evaluation involves scheduled monitoring and tracking of both functional and structural condition from its initial construction condition. Relying on surface condition alone
may not be the prudent way to understand the overall health of the pavement network with respect to remaining life, ability to carry anticipated loads, and backlog of rehabilitation needs (2). The true pavement structural condition and rate of deterioration are needed not only to plan optimal treatment activities and future budget needs but also for better assessing progress under a performance based Federal-Aid program under MAP-21.

A mechanism to include both functional measures such as ride quality and structural adequacy within the network-level pavement management system process is essential for a highway agency to provide the facility at acceptable LOS at the minimum possible cost. The functional and structural performance of a pavement during a typical analysis period subjected to a sequence of treatments is schematically illustrated in the Figure 1. The figure illustrates the difference in effect of preservation and rehabilitation activities on the functional and structural performance of the pavement. A typical new pavement (time=0) with ‘good’ structural and functional condition continues to deteriorate with traffic and climatic loading. The preservation treatment applied to the pavement section at year 4 improves only the functional condition. Though there is no improvement in structural condition, the preservation treatment potentially can retard future structural deterioration (3) illustrated by the flatter trend after year 4. The functional threshold set based on acceptable LOS triggers the treatment requirement at year 10, a rehabilitation treatment this time, improves both functional and structural performance. Two more preservation actions extends the pavement service period until the structural condition reached the terminal structural limit at year 22, when reconstruction is the only viable option. However to realize full benefit, the pavement section can be allowed in service until the functional limit is reached at year 24. Thus functional threshold is a limit for LOS beyond which the pavement should be subjected to some form of treatment and structural condition should be used along with functional threshold in integrated mechanistic and LCC analysis to arrive at optimum treatment sequence as demonstrated in subsequent sections.

![FIGURE 1 Different treatment effect on functional and structural performance.](image)

**Non-Destructive Structural Evaluation at Network Level**

Functional conditions are more commonly measured in terms of International Roughness Index (IRI) or Present Serviceability Rating. Rutting and skid resistance are also safety related functional conditions but only IRI is used in subsequent discussion for brevity. Since current
state-of-practice include regularly scheduled network pavement functional condition evaluation, this study will concentrate on structural evaluation at network level. Most highway agencies rely on an array of surrogate structural condition measures such as cracking, patching, rutting, faulting, along with functional condition measures to characterize the condition of the pavement network, set performance targets and assess future rehabilitation needs (2). However, with effective pavement preservation activities that intervene early to preserve and extend the life of pavements and increasingly thicker long-life pavements, the surrogate measures (such as surface cracks) can no longer be relied on as a reliable indicator of structural condition of the pavement structure. This is because most preservation treatments correct surface cracks by concealing them, while the bottom-up fatigue cracks continue to develop. In addition, the prevalence of top-down cracking in thicker pavements also makes it difficult to distinguish bottom-up fatigue cracking which is the common indicator of structural deterioration.

Currently, the preferred non-destructive pavement structural condition assessment is through deflection testing with Falling Weight Deflectometer (FWD). The measured deflections or indices computed from deflections are converted in to remaining structural capacity or pavement structural response and then used in PMS decision making; however no single measure or index has been widely adopted (2).

While FWD’s are the preferred device for project level structural evaluation, they are inefficient at the network level. FWD measurements are made at discrete points along the pavement sections and the equipment should remain stationary on the road during each testing point (typically 1-4 minutes, depending on the protocol). This requires traffic control and lane closures that disrupt traffic. This limits the productivity and the number of discrete points where measurements can be obtained. Traffic speed deflection devices (TSDD) were developed as a practical alternative to FWD for network level pavement structural evaluation. TRB’s second Strategic Highway Research Program (SHRP 2) R06(F) project (4) reviewed all such devices and concluded that, for network level applications, there are two potential devices currently in use – the Greenwood Engineering’s Traffic Speed Deflectometer (TSD) and the Applied Research Associate’s Rolling Wheel Deflectometer (RWD).

Building upon SHRP 2 R06(F), Federal Highway Administration’s (FHWA) current project “Pavement Structural Evaluation at the Network Level” is focused on field evaluation and validation of accuracy and precision measurements from these two devices and their effective use in pavement management applications. The successful use of TSDD for network pavement structural evaluation requires appropriate interpretation methodologies for its systematic use in pavement management.

**Deflection to Remaining Structural Capacity**

United Kingdom’s Transport Research Laboratory (5) has developed specifications for prediction of remaining structural capacity and overlay design from the standardized center deflection measured from a Deflectograph. The Deflectograph measures surface deflection under a rolling wheel at a survey speed of 1.55 mi/h (2.5 km/h) and thereby requiring traffic control and lane closures. However previous studies by the authors (6) highlighted that the center deflection is an indicator of the overall structure and it alone is not a robust measure to distinguish the structural deterioration of the asphalt concrete (AC) layer from naturally occurring spatial and seasonal variation of the subgrade. The information desired is a reliable measure of the structural condition of the AC layer as it deteriorates over time under traffic and environmental loading. While the base and subgrade may undergo seasonal changes that is
accounted for in pavement design, they don’t generally deteriorate, at least not the way the bound layers do. The curvature indices computed from two surface deflections, that can be measured with TSDD, were found to be better measures to capture the changes in the structural capacity of the AC layer at the network level and can effectively isolate the effect of natural variation in unbound layer modulus. Curvature indices are computed as the difference between the deflection at the center and at an offset distance. South Africa’s technical recommendations for highways (7) developed charts to estimate structural capacity of each pavement layer using FWD curvature indices.

A comprehensive database was developed with 15,000 simulated pavement structures covering a wide range of layer thickness and stiffness (6). Layered elastic analysis program JULEA (8) was used to compute surface deflection at typical FWD sensor spacing and horizontal tensile strain at bottom of the AC layer (referred as fatigue strain subsequently for brevity). The Asphalt Institute (AI) fatigue equation (9) was used in the database to determine the relationship between the surface curvature index (SCI) and remaining structural capacity of the pavement in terms of Equivalent Single Axle Loads (ESAL’s) as shown in Figure 2. The AC modulus is grouped in the range typically observed in new, good, moderate and poor asphalt layers so that appropriate selection of AC modulus range is possible without any additional field evaluation. The coefficient of determination ($R^2$) for the relationship in each condition is shown within parenthesis in the legend.

**Deflection to Pavement Structural Response**

Modern mechanistic-empirical (M-E) pavement analysis tools, such as MEPDG (10) and CalME (11), use incremental damage analysis to evaluate a pavement section adequacy for the defined distress thresholds. These tools divide the design period in to a number of equal time increments and model the pavement structure at each increment through models that incorporate the effect of accumulated aging, climatic and traffic loading on an in-service pavement. The tools then compute the fatigue strain at each increment and fatigue damage using calibrated equations of the form similar to AI fatigue equation (9). The computed damage is then used along with empirical transfer functions to compute bottom-up fatigue cracking as a function of time throughout the design period. The previous study by the authors (6) conceptually showed that the fatigue strains estimated with TSDD measured curvature indices (such as SCI) are effective structural performance indicators of in-service pavements and the relationship was validated using advanced modeling. The study also presented a similar relationship developed for FWD loading condition that was validated using field measured FWD deflection and fatigue strain.
FIGURE 2  Remaining structural capacity design charts developed from pavement structure database. Note: 1ksi = 6.895MPa

Illustration
Two suggested interpretation methodologies are demonstrated with a three layer pavement section given in Table 1. The CalME program was used in this effort as it can account for the continuous deterioration of the pavement structure over the design period in addition to seasonal variation. It can also analyze a sequence of treatments. The default layer material properties from CalME were used in the analysis.

TABLE 1 Pavement section used in CalME

<table>
<thead>
<tr>
<th>Layer No</th>
<th>Material</th>
<th>Thickness, inch (mm)</th>
<th>Modulus, ksi (MPa)</th>
<th>Poisson's Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HMA Type A 3/4” PG 64-22 AAC AAA</td>
<td>8 (203.2)</td>
<td>612.8 (4,225)</td>
<td>0.35</td>
</tr>
<tr>
<td>2</td>
<td>AB-Class 2</td>
<td>10 (254)</td>
<td>43.5 (300)</td>
<td>0.35</td>
</tr>
<tr>
<td>3</td>
<td>CL</td>
<td>-</td>
<td>10.2 (70)</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Figure 3(a) shows deterioration in each pavement layer represented by layer modulus over the 30 year analysis period. The figure shows the modulus value for the same month in each year, seasonal variation is not included for clarity. The AC layer shows an initial increase in modulus due to aging followed by gradually decreasing modulus due to progressive deterioration of the asphalt layer from traffic and environmental loading. The CalME predicted rutting and bottom-up fatigue cracking are Figure 3(b). CalME deterministic analysis does not compute international roughness index (IRI). Therefore, the same pavement section was used in MEPDG to compute IRI shown in Figure 3(c). The performance threshold for fatigue cracking, total rutting and IRI are defined at 0.15 ft./sq. ft. (0.5m/sq. m), 0.4 inch (1cm) and 170 inch/mile (2.7m/km), respectively. The corresponding performance period computed are 17, 23 and 20 years respectively.
FIGURE 3  Predictions from M-E tools (a) CalME predicted pavement layer structural deterioration (b) CalME predicted distress. (c) Predicted IRI from MEPDG. Note: 1ksi = 6.895MPa, 1inch = 25.4mm, 1ft/sq.ft=3.28m/sq.m., 1inch/mile=63.36m/km.

Asphalt layer modulus computed by CalME over 16 years of service life before fatigue cracking reaches the defined threshold value is shown in Figure 4(a). This is also shown earlier in Figure 3(a) in logarithmic scale. Figure 4(a) also shows the cumulative traffic loading in
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ESAL’s as computed by CalME. The pavement layer moduli at the same month over the analysis period computed as part of the CalME incremental analysis method was used in the JULEA program to compute SCI and fatigue strain as shown in Figure 4(b).

The design chart presented in Figure 2 can be used to compute the remaining structural capacity in terms of ESAL’s for the measured SCI values. For example, at year 2 after initial aging, the SCI is 1.5 mils (0.038mm) (Figure 4(b)), AC layer modulus is 720 ksi (4,964 MPa) (Figure 4(a)) and when used in Figure 2 design chart tracing AC modulus range of 500-1000 ksi (3,447-6,894MPa), the corresponding ESAL’s is 21 million. At year 16, the SCI is 2.6 mils (0.0635mm) (Figure 4(b)), AC layer modulus is 330 ksi (2,275 MPa) in the (Figure 4(a)) and when used in Figure 2 design chart tracking AC modulus range of 300-500 ksi (2,068-3,447MPa), the corresponding ESAL’s is 8 million. Thus from the design chart, the pavement has been subjected to 13 million (=21-8) ESAL’s loading in 14 (=16-2) years. From CalME analysis, for the same period, it can be seen that the pavement has carried 13.5 million ESAL’s (15.1 and 1.6 million at year 16 and 2, respectively) as shown in Figure 4(a).

Figure 4(b) also contains the fatigue strain predicted from SCI using relationship developed in an earlier study (6) that shows a similar trend. SCI is one of the indices that can readily be computed from the current TSDD measurements. The inset in the Figure 4(b) also shows the onset of fatigue cracking that appears on the surface only at the 11th year, while the fatigue strain can construe the continuous deterioration in the AC layer. Figure 4(c) illustrates the fatigue strain based performance prediction based on as-designed values computed by the M-E tool (triangle marker) as part of fatigue damage computation procedure. Figure 4(c) also shows fatigue strain that would be estimated from the periodic TSDD measurements (eg. SCI) for a pavement performing ‘better’ and ‘worse’ than the as-designed. The figure shows the corresponding difference in predicted performance period. It is envisioned that once the accuracy of fatigue strain derived from TSDD measurements has been validated with field measurements through the FHWA research effort, fatigue strain computed from periodic TSDD monitoring can form the basis of flexible pavement structural performance prediction and for determining future structural rehabilitation needs and timing. It is understood that the performance prediction should account for observed performance to-date but also future uncertainties in traffic and environmental loadings and this is one of the consideration in the implementation methodology being developed under of the ongoing FHWA research project.

INTEGRATED MECHANISTIC AND LCC ANALYSES IN SYSTEM OPTIMIZATION OF TREATMENT STRATEGY
This section demonstrate the methodology that integrate mechanistic and LCC analyses to determine the optimum treatment sequence that can be applied to the evaluated pavement section over the analysis period to maintain it at or above the required LOS at the minimum practical cost. LCC (12) analysis is an engineering economic analysis tool useful in comparing the relative economic merits of competing construction or rehabilitation design alternatives for a single project. Mechanistic analysis tools capable of incorporating a range of future treatments during design can be used to determine structural life extension from a selected treatment at a given condition. The estimated benefit (life extension) combined with treatment cost can be used in the LCC analysis to identify the optimum treatment sequence. Mechanistic analysis also enables the quantification of the monetary loss of delaying the optimum treatment.
FIGURE 4  Demonstration of interpretation methodology for TSDD measurement (a) Asphalt layer deterioration and cumulative ESAL’s over service period (b) Illustration of SCI and its relationship with fatigue strain (c) Performance prediction based on fatigue strain estimated from TSDD measurement. Note: 1ksi = 6.895MPa, 1ft/sq.ft=3.28m/sq.m., 1mils =0.0254mm.
In contrast to surface condition measures, such as cracking, that becomes ineffective as an structural condition indicator of the pavement system as a whole once new treatments are applied, the proposed methodology based on fatigue strain computed from TSDD measured deflections is able to continuously track the structural deterioration of the pavement system as a whole. This includes, contributions from future treatments, both rehabilitation treatments that add to structural capacity and preservation actions that often slow down further deterioration.

A number of treatment alternatives are possible when forecasting the pavement maintenance strategy. The selection of treatment and its performance is a function of the pavement condition at the time of application. An overlay at time ‘t’ will perform better than the same treatment applied at time ‘t+n’ when the pavement structural condition has further deteriorated. Preservation activities, though do not improve the structural capacity of the pavement, do often reduce the rate of structural deterioration. National Cooperative Highway Research Program (NCHRP) 1-48 (3) study identified the data requirements for incorporating preservation treatment effects in the MEPDG analysis. Mandapaka et al. (13) illustrated the use of integrated CalME and LCC analyses in selecting an optimum maintenance and rehab strategy for a flexible pavement sections.

The pavement section presented in Table 1 was used again to illustrate the methodology. Based on structural and functional condition at the time of evaluation, a sequence of treatment strategy ranging from preservation to reconstruction has to be identified over the analysis period for the pavement section. The above CalME analysis with a defined fatigue cracking threshold would necessitate the application of structural overlay at the 17th year. The Table 2 summarizes the life extension computed by CalME for the 1.2 inch overlay. Nevertheless, CalME analysis is repeated at different period to identify the optimum timing for the structural overlay. The overlay applied at 12th year before the appearance of surface cracking has the maximum life extension. In this example, the treatment can be delayed till 20th year when IRI (functional) threshold will be reached. However, 1.2 inch overlay might not be effective and thicker overlay (3 inch) is needed at 20th year due to continuous pavement deterioration. The total life in the table is computed as the sum of the treatment year and life extension obtained by the treatment application.

### TABLE 2 Identification of optimum treatment with LCC analysis

<table>
<thead>
<tr>
<th>Overlay Treatment</th>
<th>Cracking ft/ sq.ft</th>
<th>Life Extension, year</th>
<th>Total Life, year</th>
<th>Treatment Cost, million USD</th>
<th>NPV, million USD</th>
<th>Total NPV, million USD</th>
<th>EUAC, million USD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2inch @ 17year</td>
<td>0.15</td>
<td>10</td>
<td>27</td>
<td>1</td>
<td>0.513</td>
<td>7.213</td>
<td>0.442</td>
</tr>
<tr>
<td>1.2inch @ 12 year</td>
<td>0.01</td>
<td>17.5</td>
<td>29.5</td>
<td>1</td>
<td>0.625</td>
<td>7.325</td>
<td>0.427</td>
</tr>
<tr>
<td>1.2inch @ 20 year</td>
<td>0.59</td>
<td>2.5</td>
<td>22.5</td>
<td>1</td>
<td>0.456</td>
<td>7.156</td>
<td>0.488</td>
</tr>
<tr>
<td>3.0inch @ 20 year</td>
<td>0.59</td>
<td>12</td>
<td>32</td>
<td>2.5</td>
<td>1.141</td>
<td>7.841</td>
<td>0.439</td>
</tr>
</tbody>
</table>

Note: 1inch =25.4mm, 1ft/sq.ft=3.28m/sq.m.

LCC analysis was conducted to identify the optimum overlay thickness and time. Cost for initial construction and 1.2 inch overlay were assumed as $6.7 million and $1 million, respectively. Net present value of the treatment cost and equivalent uniform annual cost (EUAC) were computed using a discount rate of 4%. The EUAC is lowest when the overlay is
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applied at 12th year and is the optimum action and timing when fatigue cracking has not propagated to the surface.

The LCC analysis shows that treatment applied at a predefined cracking threshold might not be an efficient maintenance model. The application of TSDD in structural evaluation will enable the ability to intervene at optimum time even before the surrogate structural measures from surface distresses can detect deterioration.

Only one rehab activity was used in Table 2 for brevity. However in reality, a series of preservation/rehab/reconstruction activities will be used as part of a treatment “strategy” to identify the optimum series of treatment types and timings. For illustration, CalME program is used to analyze the above pavement section with three structural overlays at year 17, 27 and 42. Figure 5 shows typical deterioration of AC layer modulus for both initially constructed and the consecutive AC overlay layers over a 50 year analysis period. As before, CalME computed individual layer modulus values for the same month each year over the analysis period are used in JULEA to compute the fatigue strain in the initial AC layer and deflection values at center and at 12 inch in front of the dual tire load. These two deflections measurements that can be measured by TSDD are used in fatigue strain-SCI relationship developed in the previous study (6) to predict the fatigue strain. Figure 5 also shows comparison of the fatigue strain computed by JULEA and estimated using fatigue strain-SCI relationship. The figure demonstrates that the periodic measurements using TSDD over the service life of the pavement can be used to assess any differences in pavement structural performance arising from as-designed versus as-constructed, and assumed versus actual traffic, and climate effect, and future treatments can be modified as necessary.

FIGURE 5 Evaluation of optimized treatment strategy with TSDD computed structural response. Note: 1ksi = 6.895MPa
A network level pavement evaluation and planning using above methodology will result in series of optimum treatment strategies for each pavement section. Annual budget requirement can be estimated from the summation of the treatment cost at each year for different projects in the network. Unconstrained budget scenario will allow the execution of optimum treatment for all pavement sections in the budget year. However, under constrained budget scenario the projects to be treated can be selected based on the lowest network level LCC. The projects with high treatment benefit to cost ratio can be prioritized to maximize the use of available budget, thus keeping the net network value. Projects that fall below the level of service should be treated with higher priority even though the benefit to cost ratio is lower.

**UTILIZATION OF REMAINING SERVICE INTERVAL TERMINOLOGY**

Remaining Service Life (RSL) is a commonly used measure to quantify and report the pavement condition. FHWA report (14), however, documented many issues that exist with the current RSL terminology and resulting numeric that complicate proper interpretation, interagency data exchange, and use. The report presents the implementation framework for a more consistent terminology, “Remaining Service Interval” (RSI), defined as the time remaining until a defined construction treatment and is founded on the analysis methodology presented earlier in identifying the optimum series of treatment types and timings that minimizes the LCC while maintaining the pavement section at or above acceptable LOS. Most of the typical pavement treatments can be broadly grouped in to one of the three activities demonstrated in the Figure 1 namely - preservation, rehabilitation, and reconstruction. Then the new RSI terminology would report the predicted time to preservation, rehabilitation, and reconstruction for the evaluated pavement section.

The sequence of treatment selected for the hypothetical pavement presented in Figure 1 is used here to explain the merit of RSI terminology in better communicating needed future construction events. If the integrated mechanistic LCC analysis arrived at the treatment sequence as demonstrated in the figure, the sequence can be reported as in Table 3. The treatment type and time of application are also shown in the Figure 1. It should be noted that the reported RSI values at specific construction events are only valid if the previously designed construction events are addressed as sequenced. The RSI concept has the ability to unify the outcome of different approaches to determine needs by focusing on when and what treatments are needed and the corresponding service interruption created.

**TABLE 3 Network level evaluation reported in RSI terminology**

<table>
<thead>
<tr>
<th>Pavement Section ID</th>
<th>RSI Preservation, year</th>
<th>RSI Rehabilitation, year</th>
<th>RSI Reconstruction, year</th>
</tr>
</thead>
<tbody>
<tr>
<td>US1</td>
<td>4, 14, 18</td>
<td>10</td>
<td>24</td>
</tr>
</tbody>
</table>

**SUMMARY AND RECOMMENDATIONS**

The study is an ambitious and early effort to demonstrate how recent developments in pavement evaluation and mechanistic analysis along with common LCC principle can be taken advantage to meet the relevant MAP-21 objectives. It is demonstrated that the deflection indices derived from TSDD measurements are effective leading indicators of in-service pavements structural
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performance and are reasonably well related to fatigue strain. However, practical application of the methodology in routine PMS applications requires the following issues to resolved:

- Mechanistic analysis should able to include the effect of common preservation activities on pavement performance. NCHRP 1-48 has identified approaches with different data intensity level to incorporate preservation in MEPDG analysis.
- The magnitude and change over time of the TSDD measurements are small hence they must be both accurate and precise for the methodologies presented in this paper for their interpretation to be robust and reliable for network level pavement structural assessment and performance tracking. The TSDD measurements are also highly sensitive to climatic conditions at the time of testing and methods to adjust them to a “standard” or “reference” condition is critical for use in pavement management.

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