Abstract
This paper addresses the use of traffic speed deflection devices for the structural evaluation of pavements at the network-level. At the heart of the decision making process is the pavement management system (PMS), which provides condition indices or scores for each pavement segment in the network. Current PMS are driven by distress and ride quality as key pavement condition indicators. Both merit emphasis within the PMS process, but another important indicator to making rational pavement investment decisions is the structural adequacy, which is often determined based on deflection testing.

Keywords: Traffic speed, deflection; network-level structural adequacy, pavement management system

1. Introduction

The most commonly used deflection-testing device at present is the Falling Weight Deflectometer (FWD), but testing with this device comes with complications including traffic disruptions and production rates lower than those associated with a continuous testing operation. These shortcomings are important in terms of network-level PMS applications, which require information on large pavement networks. Organizations in the USA and Europe have developed devices that can measure pavement deflections at posted traffic speeds.

Recognizing the potential benefits of these devices, the US Federal Highway Administration (FHWA) commissioned a study to assess and evaluate the capabilities of existing devices and to develop methodologies for enabling their use for pavement structural evaluation at the network-level. The ultimate goal of the study was to establish a reliable measure of pavement structural condition based on traffic speed deflection technology.

2. Field Study

It was concluded based on the literature reviewed and interview findings that both the Applied Research Associates (ARA) Rolling Wheel Deflectometer (RWD) and the Greenwood Traffic Speed Deflectometer (TSD), shown in Figure 1, were potentially viable devices that merited further evaluation [1]. A plan was developed for conducting field trials to verify that the two traffic speed deflection devices (TSDD) met a minimum set of specifications – such as accuracy and precision – related to the structural evaluation of pavements at the network-level.

The MnROAD facility in Minnesota, USA was selected as the primary site for the field trials since it provided a multitude of test sections in one location as well as a wealth of readily available information, including pavement structure, pavement condition, and environmental and dynamic load response data. In addition, a 29-km loop near the MnROAD facility was tested which provided more realistic test sections.
Four geophones and one accelerometer per site were installed to measure deflection parameters at three flexible pavement sections. The performance of each sensor was then verified using an FWD. The performance of each TSDD was evaluated based on a number of factors, but most importantly its accuracy and precision. Accuracy was established by statistically comparing the results measured with the embedded sensors with those reported by the TSDDs on three separate repeat passes. The precision analysis included almost all cells at the MnROAD facility. The TSDDs made up to five passes at two to three different speeds and at two times of the day (early morning and late afternoon). Statistical analyses were then carried out between each two individual pairs of data collected in different passes. While the performance of the RWD and TSD varied under different conditions, it was concluded from the analyses of the field trial data that the accuracy and precision of both devices were acceptable for network-level evaluation.

### 3. Numerical Analyses

The 3D-Move software [2], which estimates dynamic responses at any given point within the pavement structure using a continuum-based finite-layer approach, was calibrated for use in the development of a methodology for incorporating TSDD measurements into network-level PMS applications. There was a good match between the deflection parameters computed with 3D-Move and measured with embedded sensors.

The 3D-Move program was then used to explore relationships between load-induced pavement structural-related responses (i.e., the maximum tensile strain at the bottom of the hot-mix asphalt [HMA] layer and the vertical compressive strain on top of the subgrade) and the corresponding surface deflection basin-related indices. From numerous deflection-based indices have been proposed as strong predictors of the critical structural-related responses of the pavements, 75 indices were investigated [1]. The most relevant indices are presented in Table 1. To confirm the adequacy, applicability and validity of the indices, Monte Carlo simulations were conducted using a JULEA-generated database. That database was used to develop relationships between fatigue strain and the recommended indices.

The recommended indices were then ranked by their ability to estimate fatigue strain. The deflection slope index DSI4-12, formulated as part of the study, was found to be the most appropriate index, regardless of HMA thickness, and hence it is recommended for use in network-level PMS applications. The surface curvature index SCI12 performed nearly as well, and hence it could also be considered. The TSD accuracy and precision results from the field trials were integrated with the appropriate indices to assess their practicality and robustness (Figure 2). The most robust indices include four deflection slope indices (DSI), tangent slope (TS), and area under pavement profile (AUPP).
Table 1. Deflection basin indices used in the evaluation

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Index used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius of Curvature, FHWA</td>
<td>$R = r^2/(2 , D_0(1-D_r/D_0))$</td>
<td>R1&lt;sub&gt;12&lt;/sub&gt; R1&lt;sub&gt;8&lt;/sub&gt;</td>
</tr>
<tr>
<td>Radius of Curvature, HORAK</td>
<td>$R2 = r^2/(2 , D_0(D_0/D_r-1))$</td>
<td>R2&lt;sub&gt;12&lt;/sub&gt;</td>
</tr>
<tr>
<td>Surface Curvature Index</td>
<td>SCI = $D_0 - D_r$</td>
<td>SCI&lt;sub&gt;12&lt;/sub&gt; SCI&lt;sub&gt;8&lt;/sub&gt;</td>
</tr>
<tr>
<td>Deflection Slope Index</td>
<td>DSI&lt;sub&gt;4-r&lt;/sub&gt; = $D_4-D_r$</td>
<td>DSI&lt;sub&gt;4-8&lt;/sub&gt; DSI&lt;sub&gt;4-12&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>DSI&lt;sub&gt;8-r&lt;/sub&gt; = $D_8-D_r$</td>
<td>DSI&lt;sub&gt;8-12&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>DSI&lt;sub&gt;12-r&lt;/sub&gt; = $D_{12}-D_r$</td>
<td>DSI&lt;sub&gt;12-24&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>DSI&lt;sub&gt;24-r&lt;/sub&gt; = $D_{24}-D_r$</td>
<td>DSI&lt;sub&gt;24-36&lt;/sub&gt;</td>
</tr>
<tr>
<td>Tangent Slope</td>
<td>TS = (dD/dr)</td>
<td>TS&lt;sub&gt;4&lt;/sub&gt; TS&lt;sub&gt;8&lt;/sub&gt; TS&lt;sub&gt;12&lt;/sub&gt; TS&lt;sub&gt;24&lt;/sub&gt;</td>
</tr>
<tr>
<td>Area Under Pavement Profile</td>
<td>AUPP = $(5D_0 - 2D_{12} - 2D_{24} - D_{36})/2$</td>
<td>AUPP</td>
</tr>
</tbody>
</table>

![Figure 2. Overall field performance of indices](image-url)

4. Conclusions and Future Directions

The identification of indices that best relate TSDD measured deflections to horizontal strains at the bottom of the HMA layer is an important step, but more is needed for the use of these indices in support of the network-level PMS applications. Ideally, it is desirable to be able to determine whether the different pavement network segments are candidates for preservation, maintenance, rehabilitation, reconstruction or do nothing (i.e., they are adequate as is). As a
minimum, these steps need to be able to provide information on whether the pavement is structurally sound for the anticipated traffic or not. Another critical consideration is the spatial averaging of the data. For effective utilization, spatial statistical analysis and segmentation of the TSDD data are necessary.

While different approaches are possible, the one illustrated in Figure 3 is recommended for network-level PMS applications and decision-making. TSDD testing has come a long way over the past decade and the technology of these devices is ready for use in network-level pavement structural evaluations. However, the validation and/or calibration of the recommended deflection indices and implementation procedures needs to be done using field data collected on highway agency networks. Significant equipment improvements are also possible. For example, the data collected by TSDDs are averaged over distance. The shorter the averaging distance is, the more detailed the analysis will be, but averaging is necessary for agencies to work with a manageable amount of data.

![Figure 3. Idealized PMS flowchart containing TSDD structural evaluation component](image)

**Acknowledgement**

The authors are grateful to the US Federal Highway Administration for providing the opportunity to conduct this study as part of the “Pavement Structural Evaluation at the Network Level” project. The findings and opinions expressed here however are those of the authors, and not necessarily the views of the sponsoring agency.

**References**
