A Practice towards Pavement Monitoring and Evaluation

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ABSTRACT

Pavement condition monitoring and evaluation is important in many areas of pavement engineering, especially in pavement management. The in-service performance of the pavement depends on consistent, cost-effective and accurate monitoring of condition for early scheduling of repair and maintenance. Non-Destructive Testing (NDT) has played a major role in pavement condition monitoring, assessments and evaluation accomplishing continuous and quick collection of pavement data. The analysis of this data can lead to indicators related to trigger values (criteria) that define the pavement condition based on which the pavement “health” is perceived helping decide whether there is the need or not to intervene in the pavement. However, in order to support effectively the implementation of pavement management activities, sometimes there is the need to apply a framework for pavement monitoring and evaluation that highway/road agencies can adapt as the case may be. For this purpose the present research concerns the development of a practice towards pavement monitoring and evaluation that is outlined by four basic pillars: NDT data, periodic monitoring, reliable analysis methods and weighed evaluation criteria. The proposed practice referred with the acronym PAME (PAvement Monitoring and Evaluation) is implemented on a highway using individual data i.e. traffic (ESALs), layers thickness, deflections and roughness in order to determine the optimum section strategies and priority interventions. More details are included in the paper.
The pavement management activities consist mainly of three sequential yet interconnected processes: condition assessment, performance prediction and needs analysis (1). They aim at assessing the appropriate maintenance and rehabilitation strategies on the basis of given budget constraints, identifying life-cycle cost alternatives and determining the optimum time for maintenance and rehabilitation interventions. These can be accomplished, through an effective Pavement Management System (PMS), which can be described as a set of tools or methods that can assist decision makers in finding cost effective strategies for evaluating and maintaining pavements in a serviceable condition over a given period of time. Preserving pavements in an appropriate manner, extends their service life, and most importantly improves users’ safety and saves public resources, which is the goal of an ideal pavement management system (2).

However, for the prosperous operation of a PMS it is necessary to have appropriate procedures for pavement monitoring and evaluation, which is important in many areas of pavement engineering. Non Destructive Testing (NDT) has played a major role in pavement condition monitoring, assessments and evaluation accomplishing continuous and quick collection of pavement data. The analysis of this data can lead to indicators related to trigger values (criteria) that define the pavement condition based on which the pavement “health” is perceived helping decide whether there is the need or not to intervene in the pavement. The accomplished perception appoints required management activities for preserving pavements in favor not only of the involved highway/road agencies but also of users’ service.

In order to support effectively the implementation of pavement management activities, sometimes there is the need to apply a framework for pavement monitoring and evaluation that agencies can adapt as the case may be. For this purpose the present research concerns the development of a practice towards pavement monitoring and evaluation that is outlined by four basic hints: NDT data, periodic monitoring, reliable analysis methods and weighed evaluation criteria. The proposed practice referred with the acronym PAME (PAvement Monitoring and Evaluation) is implemented on a highway of approximately 80 km in length using individual data i.e. traffic (ESALs), layers thickness, deflections and roughness in order to determine the optimum section strategies and priority interventions. Thickness data is gathered using the Ground Penetrating Radar (GPR) technique (3), deflections are recorded using Falling Weight Deflectometer (FWD) testing (4), while roughness data collection is accomplished using a highway inertial profiler (5, 6).

The implementation of the developed practice in terms of supporting pavement management activities demonstrates advantages that include simplicity in application, economic benefits and familiarity and are representative of cases where few resources and minimal information requirements are available. The present paper demonstrates the implementation of the proposed practice and the related results.

PRACTICE FEATURES AND DEVELOPMENT

Required Data

The main objective of the developed practice is the periodic evaluation of the structural and functional condition of the existing pavement. Based on this the pavement performance affected by changes of environment and accumulation of traffic can be predicted. Thus, an accurate and
reasonable evaluation is important to increase the pavement service life with adequate rehabilitation. For this purpose, several data need to be collected taking into consideration that “good” data is very important in providing effective pavement management. In terms of the pavement structural evaluation, the minimum required individual data include traffic information, pavement layers thickness and pavement deflection records. As far as the pavement functional evaluation is concerned, it is indispensable to collect roughness data that best reflects the public’s perception of the overall condition of a pavement section. Of course functional evaluation could benefit from additional data such as rutting measurements or surface distress records for supporting pavement management activities comprehensively; roughness data is considered as minimum required data addressing the simplicity of the developed practice.

All needed pavement data is gathered using NDT. The GPR technique (7) accomplishes the acquisition of accurate, continuous pavement layer thicknesses data. It is worth to mention that a GPR system consists of an antenna unit, a transmission/reception unit, a control unit and a storage/display unit (Figure 1). The antenna unit can be a single antenna that transmits and receives radar signals or two separate antennas one for transmission and one for reception. In both cases the antennas must be lightweight and maneuverable so that they can be easily positioned over the area under investigation. The transmission/reception unit consists of a transmitter for signal generation, a receiver for signal detection and timing electronics for synchronizing the transmitter and the receiver. The control unit is the operator interface that controls the overall operation of the GPR system and sends the received data to the data storage and display unit.

Through GPR technique ‘black’ spots locations can be identified and then, these locations can be further examined based on FWD testing or even by coring. Additionally, GPR provides thickness data which is further used in pavement mechanistic analysis models incorporated with the FWD technique, which addresses the evaluation of the physical properties of the pavement structure (8). FWD simply generates a load pulse by dropping a weight on a damped spring system mounted on a loading plate (Figure 2). The falling mass, the spring system (rubber buffers) and drop height can each be adjusted to achieve the desired impact loading on the pavement. Vertical deflection peaks are measured at the centre of the loading plate and at multiple radial positions by a series of deflection sensors. The impulse load acting on the pavement causes a "wave front" of recoverable deformations, or deflections, that spread out
from the centre of the load. Both the peak impulse load (force) and maximum vertical deflections of the "wave front" are measured at multiple radial distances from the load centre. These deflections, considered as a function of the applied impulse load, provide an indication of the structural strength of the pavement. Taking into account available traffic information and considering the GPR thicknesses, FWD deflections are analyzed towards the estimation of pavement bearing capacity, which results or not to the need for repair.

![FWD testing diagram](image)

**FIGURE 2 FWD testing.**

As far as roughness data collection is concerned, high speed inertial profilers, which are the most technologically advanced and most widely used systems, are incorporated in the developed practice. They record the characteristics of the pavement surface profile at high speeds by using accelerometers and sensors (lasers), which measure the vertical distance between the accelerometer and the surface. The profilers usually have a beam as a basic unit that has integrated electronic laser sensors and accelerometers. The beam is adapted to be placed on the rear or on the front of a suitably modified vehicle, so that it provides a plane surface for the installation of the sensors (Figure 3). The measured parameters are processed and analyzed, in order to produce the longitudinal surface profile of the surveyed pavement and then determine the International Roughness Index (IRI) \(^{(9, 10)}\).

![High-speed inertial profiler](image)

**FIGURE 3: High-speed inertial profiler.**

It is summarized that the proposed practice for pavement monitoring and evaluation involves the pavement structure capacity and the user-related factors of roughness towards the determination of optimum section strategies and priority interventions in an optimum way.
**Setting Pavement Monitoring and Evaluation**

In order to set the steps that describe the developed practice for pavement monitoring and evaluation it is essential to make clear that two sub-procedures are addressed. These concern the structural and the functional condition of the investigated pavement(s). On this basis setting pavement monitoring and evaluation is as follows.

Investigation of the structural condition of the pavement may be performed, based on the guidelines of (11). Initially, the section under investigation is divided into homogeneous subsections, based on pavement layer thicknesses, traffic and deflection data. The final segmentation of the section is a combination of the intermediate divisions (Figure 4).

<table>
<thead>
<tr>
<th>Layer thicknesses</th>
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</thead>
<tbody>
<tr>
<td>Centre deflection</td>
</tr>
<tr>
<td>(D₀)</td>
</tr>
<tr>
<td>Traffic</td>
</tr>
<tr>
<td>Final segmentation</td>
</tr>
<tr>
<td>(5 subsections)</td>
</tr>
</tbody>
</table>

**FIGURE 4 Road section segmentation.**

Concerning the section division based on deflection data, a worldwide used index coming from the FWD measurements is used (D₀ index) (11, 12). The D₀ index is based on the maximum centre deflection measured with the FWD and represents the overall structural condition of a pavement. For the estimation of this index, the measured deflection should be normalized to the target load of the testing and to a reference temperature (usually 20°C) using suitable international factors (11). This is essential, since the mechanical characteristics and the behavior of the asphalt mixes are significantly influenced by temperature and also deflections are dependent on the imparted load.

In order to divide the section into homogeneous subsections based on the three above mentioned parameters, several statistical techniques may be used. One of these techniques is the cumulative sum (Cum Sum) method. This method requires the plot of the cumulative sums of the deviations from the mean of a parameter and indicated homogeneity when the slope of the line connecting all cumulative sum values changes. However the difference between two adjacent sections may not be significant and the statistical difference of adjacent sections can be checked with the T-test. For each subsection, the number of measurements, the average, the median and variance are calculated. By estimating the weighted variance of two adjacent subsections, their homogeneity can be determined.

After the final segmentation of the main section into homogeneous subsections, an evaluation of the structural condition of each individual uniform subsection can be performed, utilizing international experience and practice (11, 12, 13). Among these it is believed that by setting the 85% percentile of the D₀ values (only 15% of the values are higher) as representative of the in subject subsection we can achieve more objective strengthening design analysis (i.e. overlay thickness). Dependent on the authorities the analysis could be performed as well for even higher percentile values, but not less.
The strengthening design results in terms of overlay needs is followed by the longitudinal profile evaluation of pavement surfaces of each subsection, based on statistical analysis of the measured IRI values, which specifies the users’ perception of ride quality. IRI is a widely used and well established roughness index since it is considered to be a good indicator of pavement condition in respect to road roughness (14, 15, 16). IRI is a key decision criterion for the selection of deficient roads and is also accepted as an index for construction quality evaluation in regards to surface finish (17).

For the evaluation three criteria are established, based on critical IRI values for particular characteristic variables and confidence levels (i.e. $IRI_{cr1}$, $IRI_{cr2}$, $IRI_{cr3}$). It is worth mentioning that the characteristic critical values are mostly dependent on the road class classification defined by the traffic level (i.e. Average Annual Daily Traffic, % trucks, ESALs). The statistical analysis comprises the determination of the theoretical distribution function best fits the distribution of the obtained IRI data and the calculation of the characteristic variable values at the relevant confidence levels (i.e. $IRI_{85}$, $IRI_{95}$, $IRI_{100}$).

### TABLE 1 Characteristic Basic Variables, Recommended Values and Confidence Levels

<table>
<thead>
<tr>
<th>Characteristic base variables</th>
<th>Recommended values and confidence levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>$IRI_{cr1}$</td>
<td>Characteristic acceptability limit value</td>
</tr>
<tr>
<td>$IRI_{cr2}$</td>
<td>Upper limit value of a confidence interval</td>
</tr>
<tr>
<td>$IRI_{cr3}$</td>
<td>Fit for use – limit value</td>
</tr>
</tbody>
</table>

### TABLE 2 Criteria for Longitudinal Roughness Evaluation

<table>
<thead>
<tr>
<th>Criteria for longitudinal roughness evaluation</th>
<th>Condition</th>
<th>Confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion 1</td>
<td>$IRI_{85} \leq IRI_{cr1}$</td>
<td>85%</td>
</tr>
<tr>
<td>Criterion 2</td>
<td>$IRI_{95} \leq IRI_{cr2}$</td>
<td>95%</td>
</tr>
<tr>
<td>Criterion 3</td>
<td>$IRI_{100} = IRI_{cr3}$</td>
<td>100%</td>
</tr>
</tbody>
</table>

By using the three above criteria the required interventions can be determined. More precisely, there are three kinds of the evaluation outcome (Figure 5). The first corresponds to no need for intervention, while the other two correspond to two warning procedures of different severity (1<sup>st</sup> LEVEL and 2<sup>nd</sup> LEVEL).
FIGURE 5 Flowchart of PAvement Monitoring and Evaluation (PAME).
The functional evaluation procedure, as illustrated in Figure 5, follows the pavement structural evaluation. In case the structural evaluation has shown no need for intervention, the functional evaluation is performed immediately. In the case where intervention for structural reasons is required, the roughness profile evaluation has to be performed after the implementation of the required intervention.

In case that the sections under investigation are structurally adequate and also fulfil the criteria for the roughness evaluation, the PAME procedure is completed. Otherwise, maintenance treatments for the improvement of the ride quality are suggested and the roughness evaluation follows the implementation of the intervention measures.

The proposed procedure can be repeated periodically for future pavement evaluation in terms of supporting pavement management activities.

APPLICATION

Test Site
A pilot implementation of the PAME practice was carried out along a highway road section, in order to verify the applicability of the proposed methodology. For that purpose, NDT data (i.e. deflection, layer thicknesses and roughness) along a heavy-duty flexible pavement and traffic information was collected and further analyzed.

FIGURE 6 NDT systems used for data collection.
NDT testing using the systems of the Laboratory of Highway Engineering of National Technical University (NTUA) (Figure 6) was undertaken along the outer traffic lane, since that lane carries most of the truck traffic and thus exhibits much more load-associated distress than the inner lane. The FWD (18) measurements were performed at 200m spacing in the right wheel path of the lane, while the GPR (19) records were continuous along the entire length of the lane. During the FWD testing, the in-situ pavement temperatures and air temperatures were recorded as well for analysis purpose. Roughness data was recorded using the Road Surface Profiler (RSP) which belongs to the high speed inertial profiler category (20).

Data Analysis and Results
The structural evaluation of the highway pavements condition follows the segmentation of the road section into homogeneous subsections, which have approximately uniform pavement structure and bearing capacity. The final segmentation is based on the division of the main section to subsections according to the normalized deflection values ($D_0$ index), asphalt layer thickness and traffic using suitable statistical reliable technique (i.e. Cum Sum method).

Figure 7 illustrates the division of the road section according to the asphalt concrete layer thicknesses into (eight) subsections, based on the statistical values (si) derived from the implementation of the Cum Sum method.

![FIGURE 7 Segmentation of road section based on AC layer thickness.](image)

The implementation of the Cum Sum method according to the $D_0$ index and the traffic as well, leads to the final segmentation of the road section into nine uniform subsections (SS_1-SS_9), illustrated in Figure 8.
After defining the homogeneous subsections, a structural evaluation analysis is conducted, in order to assess the in situ pavement layer properties (i.e. backcalculated moduli). This information is subsequently used to determine the bearing capacity and calculate the overlay requirements over a 20-year design period.

**FIGURE 8** Final road segmentation based on AC layer thicknesses, $D_0$ index and traffic.

**FIGURE 9** Overlay requirements per subsection (SS).
The structural analysis results (Figure 9) indicate that seven out of nine subsections seem to be structurally adequate, while the two remaining (SS_2 and SS_8) need to be structurally reinforced.

Further to the structural evaluation, a longitudinal profile evaluation of pavement surfaces of each subsection is conducted, after the implementation of the intervention measures, where needed. The functional evaluation is based on statistical analysis of the measured IRI values. Within the scope of the current application, for single values of the IRI index, a representative longitudinal road segment was adopted with the length of 10 meters.

By analyzing the distribution of the relative frequencies of the measured IRI values of the subsections SS1-SS9 using the best fit distribution software, the probability density function type log-normal distribution has shown the best approximation, according to Kolmogorov-Smirnov test results (Figure 10). The theoretical distribution function best fits the distribution of the obtained IRI data is then used to calculate the characteristic variable values at the recommended confidence levels in order to evaluate the recommended criteria.

**FIGURE 10 Best fit probability distribution function.**

![Graphic representation of the best fit probability distribution function with a log-normal distribution.](image_url)
TABLE 3 Longitudinal Roughness Evaluation Results

<table>
<thead>
<tr>
<th>Motorway Subsections</th>
<th>Confidence levels and characteristic variable values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>85%</td>
</tr>
<tr>
<td></td>
<td>IRI_{85}</td>
</tr>
<tr>
<td>SS1</td>
<td>1.0</td>
</tr>
<tr>
<td>SS2</td>
<td>0.8</td>
</tr>
<tr>
<td>SS3</td>
<td>0.7</td>
</tr>
<tr>
<td>SS4</td>
<td>1.0</td>
</tr>
<tr>
<td>SS5</td>
<td>0.9</td>
</tr>
<tr>
<td>SS6</td>
<td>0.9</td>
</tr>
<tr>
<td>SS7</td>
<td>0.9</td>
</tr>
<tr>
<td>SS8</td>
<td>0.9</td>
</tr>
<tr>
<td>SS9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The results of the subsection’s functional evaluation define that the pavement condition is adequate and there is no need to intervene in the pavement. Further to the above the proposed PAME practice is completed.

Aside from rural roadways or highways such as the one considered in the present work, the PAME approach could be used for urban roadways or even for different classifications of roadways. Thus the criteria would change depending on these items, particularly the functional criteria, since the desired performance level of IRI may be different depending on road classification. In any case the proposed practice is fairly simplistic to implement and the data feeding the evaluation is objective as opposed to many pavement condition collection methods that can be very subjective to the personnel collecting or analyzing the data.

CONCLUSIONS

PAME practice developed in the present work may be considered as a useful procedure to serve pavement management activities through the determination of optimum section strategies and priority interventions, especially in situations where data availability/requirements are limited. The main requirement of PAME is the collection of NDT thickness, deflection and roughness data, which has to be analyzed properly and evaluated based on weighed criteria following a strict loop of pavement monitoring.

It seems that PAME practice can provide the decision makers with a simple and practical tool for supporting pavement management activities. It can also ensure pavement agencies a cost effective use of constraint resources, which is thought to be extremely important. Moreover, the proposed methodology can be adjusted according to the road owners’ needs and the corresponding intervention strategies.
REFERENCES


