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Research

Structural Assessment of Flexible Pavements Based on the Level of Detail of Management Functions

Evaluación estructural de pavimentos flexibles basada en el nivel de detalle de las funciones de gestión

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Abstract

Context: Pavement condition data are a fundamental component of pavement management systems (PMS) and play a critical role in structural evaluation. The quality of these data directly influences decision-making processes at the network, project, or research level particularly regarding the pavement project life cycle.
Method: This study aimed to assess 18 techniques for evaluating the structure of flexible pavements, utilizing both non-destructive (NDT) and destructive (DT) testing. Following a comprehensive review of the consulted techniques, proprietary models were developed and implemented across multiple projects to structurally evaluate in-service pavements. Statistical analysis was employed to determine the relationships between parameters, distinguishing between those based on empirical and mechanistic approaches.
Results: The application of evaluation techniques revealed that parameters such as radial strain (εrca), vertical strain (εzsr), and the structural number exhibit a strong correlation when categorized within the same approach. Conversely, their correlation is moderately strong when differing approaches are used. Additionally, models relying solely on deflection basin data demonstrated high correlation with rigorous methods that incorporate thickness data.
Conclusions: These findings underscore the practical value of the developed models in pavement management at the network level, offering cost-effective solutions that enhance the detection of structural deficiencies and inform maintenance and rehabilitation strategies.

Keywords: pavement, testing, structural models

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Resumen

Contexto: Los datos sobre el estado del pavimento son un componente fundamental de los sistemas de gestión (SGP) y desempeñan un papel importante en la evaluación estructural. Dependiendo de la calidad de la información, estos datos son valiosos para la toma de decisiones a nivel de red, de proyecto o de investigación en relación con la gestión del ciclo de vida del pavimento.
Método: El objetivo de este estudio fue evaluar 18 técnicas de evaluación estructural de pavimentos flexibles basadas en ensayos no destructivos (END) y destructivos (DT). Después de una revisión integral de las técnicas consultadas, se desarrollaron modelos propios que fueron implementados en múltiples proyectos para la evaluación estructural de pavimentos en servicio. Se empleó el análisis estadístico para determinar las relaciones entre parámetros, distinguiendo entre aquellos que se basan en enfoques empíricos y mecanísticos.
Resultados: La aplicación de las técnicas de evaluación reveló que parámetros como la deformación radial (εrca), la deformación vertical (εzsr) y el número estructural presentan una fuerte correlación cuando pertenecen al mismo enfoque. Por otro lado, su correlación es moderadamente fuerte si el enfoque difiere. Además, los modelos que se basan únicamente en datos de cuencas de deflexión se correlacionan muy bien con métodos rigurosos que también requieren datos de espesores.
Conclusiones: Los resultados resaltan el valor práctico de los modelos desarrollados para la gestión de pavimentos a nivel de red, proporcionando una solución eficiente en costos que facilita la detección de deficiencias estructurales y mejora las estrategias de mantenimiento y rehabilitación.

Palabras clave: pavimento, pruebas, modelos estructurales

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1. Introduction

Structural evaluations are conducted to assess the characteristics of pavement, focusing on the bearing capacity of the subgrade and the structural resistance of the layers composing the pavement structure. These evaluations are essential for estimating the remaining service life of the pavement (1). Various methodologies are used for structural assessment, categorized as *non-destructive* (NDT) and *destructive* (DT) tests, which allow for both qualitative and quantitative evaluations of pavement performance.

One of the most widely used NDT techniques for structural evaluation is the falling weight deflectometer (FWD), which provides the surface deflection basin – a critical dataset for identifying structural behavior parameters. These parameters facilitate qualitative and quantitative assessments of pavement conditions (2).

According to (3) qualitative evaluations are conducted using deflection bowl parameters such as the surface curvature index (SCI), the base damage index (BDI), the base curvature index (BCI), the radius of curvature (Rc), the AREA, the normalized area ratio (A'_r), the area under the pavement profile (Aupp), area indices (AI1, AI2, AI3, AI4), shape factors (F1, F2, F3), the structural index (Ie), the extensibility factor (S), the curvature factor (CF), the deflection slope (SD), the deflection ratio (DR), and the load extensibility index (LSI).

For quantitative pavement assessment, rigorous techniques utilize both deflection (NDT) and thickness (DT) data. These include the AASHTO NDT I method and the mechanistic approaches, which employ computational models to back-calculate the modulus of the layers and estimate the stress states within the structure. Additionally, some methods use closed-form direct calculation formulas based on NDT and DT data, as outlined in (4–6).

These correspond to the AASHTO 93, AASHTO NDT II, Rohde, Wimsatt, and Howard methods. Other direct calculation formulas rely exclusively on NDT deflection data as the input (5,7–12).

The application of techniques such as such as the AASHTO 93, Rohde, and mechanistic methods has been confined to project-level evaluation events for determining maintenance or rehabilitation strategies in highway concessions. Thus, their application in pavement management Systems (PMS) for planning, decision-making, or deterioration modeling remains limited.

While rigorous methods offer higher precision, their implementation demands time and financial resources, restricting their applicability to project-level management. Conversely, direct calculation methods provide advantages such as simplified formulations, rapid applicability, and reduced reliance on specialized software. In addition, by eliminating the need for thickness data, they offer lower cost and avoid the challenges associated with geotechnical exploration, which makes them valuable for network-level evaluations.

The main objective of this research is to test and validate structural evaluation techniques, which are explored in conjunction with original models and applied to in-service pavement structures. This work also introduces assessment methodologies at both the network and project levels. These methodologies facilitate performance monitoring and help to implement actions related to maintenance, rehabilitation, programming, and planning. Consequently, this document presents the results obtained through empirical and mechanistic approaches utilizing NDT and/or DT data for the assessment of structural conditions.

2. Methodology

This study employs a multi-step approach to the structural evaluation of pavements. First, a comprehensive review of various structural evaluation techniques is conducted, followed by the development of original models based on the conceptual frameworks of the reviewed methods. These techniques are classified as *empirical or mechanistic* depending on key parameters such as the structural number (SN) or the stress states (stresses and deformations), respectively.

The reviewed and developed models are then applied to pavements with an asphalt concrete wearing course supported by untreated granular materials. It should be noted that these pavements correspond to various national roads currently in service. Finally, this study assesses the feasibility of implementing these models in network- and project-level management functions within PMS.

To compare and validate the selected models, multiple structural evaluation methods are explored, incorporating both empirical and mechanistic approaches through NDT and DT testing, including the Noureldin, Yonapave, Rohde, and Howard methods, among others referenced in the introduction. While various techniques were tested – such as AASHTO NDT I and mechanistic approaches for estimating the remaining service life – the final selection of AASHTO 93 and the mechanistic (rational) approach using BISAR 3.0 was guided by three key criteria:

- *Broad international recognition*. This provides a solid and reliable basis for evaluating accuracy and applicability.
- *Extensive prior validation in the local context.*
- *Established performanc*e of other models considered and developed in this research, including those based solely on NDT data.

The studied models were constructed using an initial reference, defining ranges of variation in pavement layer thickness and modulus values. While various software tools based on linear elastic theory are available for estimating pavement stress states (*e.g.*, DEPAV, KENLAYER, WESLEA), BISAR 3.0 was selected for this study since it assesses the behavior of the studied parameters. BISAR is a well-established program suitable for the multi-layer elastic analyses aimed at effectively determining the stress states of modeled structures.

The evaluated parameters include the radial tensile strain in the asphalt pavement base (εrca), the vertical compressive strain in the subgrade (εzsr), and indices such as the SCI, the BDI, the BCI, the

Table I. Parameters of the pavement structures modeled

Layer	Thickness (cm)	Modulus (MPa)	Poisson coefficient
Asphalt concrete	5 - 10 - 15 - 20 - 30 - 45 - 60	750 - 1500 - 2250 - 3000 - 3750 - 4500	0.35
Granular	15 - 30 - 45 - 60	75 - 150 - 225 - 300 - 375 - 450	0.40
Subgrade	-	25 - 50 - 75 - 100 - 125 - 150	0.45

Aupp, and the overall AREA. This combination of parameters, as presented in Table I, resulted in a database comprising over 6000 theoretically modeled structures.

The studied roads span different geographical regions and vary in road hierarchy, including both dual and single carriageways serving primary or secondary functions, with an average length of 75 km per carriageway. These in-service structures consist of typical flexible pavements, featuring an asphalt concrete wearing course with thicknesses ranging from 5 to 40 cm, supported by granular materials of varying widths. The structural layers rest upon fine or fine-grained subgrade soils.

To perform the structural evaluation, each carriageway was segmented using the cumulative differences method, with deflection as the response parameter. This method, as outlined in the AASHTO 1993 guidelines and INVÍAS standards (*e.g.*, INV 821-13), categorizes sections with a similar structural behavior by analyzing changes in the slope of the cumulative sum parameter (Zx), derived from deflection measurements along the roadway.

Within each homogeneous unit, assuming that the deflection data approximated a normal distribution, statistical analysis was performed using metrics such as the mean, the standard deviation, and the coefficient of variation. This allowed selecting a characteristic deflection basin that represented the predominant structural behavior, resulting in a total of 160 homogeneous sections defined for this work.

The consulted structural evaluation techniques provide insights into pavement performance through both qualitative and quantitative parameters. Qualitative parameters offer an initial assessment of structural condition, serving as a foundation for quantitative modeling. These quantitative models, which incorporate condition indices, determine the pavement's structural integrity and aid in identifying whether reinforcement measures are required. The following sections will provide a detailed analysis of these models.

2.1. Empirical approach

These techniques rely on parameters thar are empirically obtained. One of these parameters is the SN, which was originally developed in the 1950s through the AASHO road test (13).

2.1.1. Structural capacity of existing or in-service pavement

It is essential to distinguish between the standard structural number (SN) and the effective structural number (SNeff). The standard SN is typically calculated during the pavement design stage, based on specified material properties including layer and drainage coefficients and layer thickness. This value serves as a preliminary estimate for dimensioning the pavement structure. In contrast, SNeff is obtained from field measurements from the existing pavement, reflecting its actual condition and structural capacity after construction, usage, and deterioration – this is traditionally determined using methods like FWD testing. Therefore, SNeff is used to evaluate the current structural adequacy and determine potential rehabilitation needs.

Acknowledging this distinction between design and evaluation parameters, the standard SN remains a fundamental concept in pavement. SN has been widely recognized as a parameter for assessing structural capacity and quantifying pavement strength. It has been adopted as a key criterion in design and evaluation processes to determine the need for reinforcement, and it has been involved in most of the deterioration models employed in PMS (14).

The effectiveness of using the SN and its variants, such as the modified structural number (SNP) and the SNeff, lies in its ability to integrate the mechanical properties of pavement layers into a quantifiable measure of resistance against traffic loads and environmental conditions. These parameters allow for structural capacity evaluation and deterioration prediction. Globally, the SNP is widely used in management models such as HDM-4, a critical tool for road investment and maintenance planning, as it can forecast performance indicators, including crack propagation and the international roughness index (IRI), support optimal resource allocation, and extend the service life of pavement.

In Colombia, consulting firms responsible for structural evaluations in road concessions routinely apply empirical approaches for maintenance management. These firms often incorporate the SNeff (typically derived using the AASHTO 93 method) into their analysis algorithms in order to assess the structural capacity and remaining service life of pavement, which aids in maintenance and rehabilitation decision-making.

Table **II** outlines the main concepts of the methods used for estimating the structural capacity of pavements in service, which are often associated with determining the SNeff.

2.1.2. Required pavement structural capacity

The structural capacity required to accommodate projected traffic demands, which considers subgrade strength, weather conditions, and performance criteria, is quantified using the structural number required (SNreq). This parameter serves as a critical measure in pavement design and evaluation, ensuring that the pavement structure meets the expected load-bearing capacity over its service life. In this study, direct calculation expressions are utilized to estimate it. These include one model developed within this research and another identified in the literature review (Table **III**).

Table II. Structural capacity of pavements in service

AASHTO 1993	
Subgrade strength	**Structural capacity of pavement**
$M_{rr} = \frac{0.24 \cdot P}{D_r \cdot r}$ (1) $r \geq 0.7 \cdot a_e$ $\geq 0.7 \cdot \left[\sqrt{a^2 + \left(H_p^3 \sqrt{\frac{E_p}{M_{rr}}}\right)}\right]$ (2)	$D_0 = 1.5 \cdot p \cdot a \cdot$ (3) $\left\{\frac{1}{M_{rr} \cdot \sqrt{1 + \left(\frac{H_p}{a} \cdot \sqrt[3]{\frac{E_p}{M_{rr}}}\right)^2}} + \left\lvert \frac{1 - \frac{1}{\sqrt{1 + \left(\frac{H_p}{a}\right)^2}}}{E_p} \right\rvert \right\}$ $SN_{eff} = 0.0045 \cdot H_p^3 \cdot \sqrt[3]{E_p}$ (4)
According to the AASHTO (American Association of State Highway and Transportation Officials), the back-calculated resilient modulus (Mrr) of the subgrade can be determined from the deflections obtained using FWD, via Eq. (1) (15). An adjustment factor (C) is applied to this expression to convert Mrr into an equivalent value measured in the laboratory (Mr). This laboratory value is intended for use in the design procedures described by the AASHTO guidelines. Further details on this can be found in (3). The deflection used for back-calculating Mrr is determined using Eq. (2).	The equivalent modulus, determined through Eq. (3), reflects the structural capacity of the existing pavement, i.e., the equivalent stiffness provided by the asphalt layer and the materials beneath it (15). The methodology proposed by AASHTO employs the SNeff to assess a pavement's structural capacity. This SNeff can be back-calculated from deflection measurements using FWD, as described in Eq. (4).
South African method	
Structural capacity of the pavement-subgrade system	
$SNC = e^{5.12} \cdot BL^{0.31} \cdot A_{UPP}^{-0.78}$ (5)	
$SNC = \sum_{i=1}^{n} a_i \cdot h_i + SN_{sg} = SN_{eff} + SN_{sg}$ (6)	$ICS = D_0 - D_{30}$ (8)
$SN_{sg} = 3.51(\log CBR) - 0.85(\log CBR)^2 - 1.43$ (7)	$A_{UPP} = \frac{5D_0 - 2D_{30} - 2D_{60} - D_{90}}{2}$ (9)
For CBR ≥ 3 for CBR < 3 equals 0 (zero)	
Through a multiple regression procedure, Schnoor and Horak developed a method for assessing the structural capacity of flexible pavements using the modified structural number (SNC) and deflection basin parameters measured via FWD. This resulted in the Regression Eq. (5), which is supported by Eqs. (8) and (9) (16). It should be noted that the SNC accounts for the subgrade's structural contribution. Therefore, to express pavement capacity in terms of the SNeff, the subgrade structural number (SNsg) must be subtracted, as shown in Eqs. (6) and (7) (4).	
Studied model	
Pavement structural capacity	

$SN_{eff} = 1.2 + 7.707H_p - 0.0013D_0 - 0.00061A_{UPP}$	(10)
Eq. (10) correlates specific parameters from the deflection basin with others that provide information about the structural response. The correlation between parameters was statistically determined based on the results of modeling various theoretical structures using the BISAR 3.0 software (3).	

Table III. Structural capacity required

Expression found in the literature	Expression developed in this study
$SN_{req} = 0.05716(\log N - 2.32\log M_r + 9.07605)^{2.36777}$ (11)	$SN_{req} = 12.547 \cdot M_r^{-0.6567} N^{0.0238 \cdot \ln M_r + 0.0685}$ (12)
Eq. (11) corresponds to a study on structural capacity conducted by the Virginia Transportation Research Council (VTRC) (17).	Using curve fitting methods, an expression was developed which relates SNreq to the design parameters of the method. This is presented in Eq. (12).

2.2. Mechanistic approach

This approach utilizes pavement mechanics to determine the relationship between the cause of loading (traffic loads) and the structural response, which is characterized by stress states (stresses, deformations, and deflections). The radial tensile strain in the base of the asphalt pavement (εrca) and the vertical compressive strain in the subgrade (εzsr) are the parameters considered in estimating structural and functional failure repetitions, respectively.

2.2.1. In-service pavement loadings

Pavement service deformations are calculated using computer programs that simulate stress states through multilayer elastic systems. In this study, the BISAR 3.0 software was employed to calculate the control parameters involved in the mechanistic method (εrca, εzsr), which are associated with fatigue and rutting deterioration (18). To calculate these parameters, regression expressions were also tested in order to predict the structural response based on certain deflection basin parameters obtained via FWD (Table **IV**).

2.2.2. Allowable pavement loads

In-service loads are estimated employing the transfer functions and correlation models presented in Table **V**.

Table IV. Loadings calculated using regression expressions

Literature model	**Study model**
$\log(\varepsilon_{rca}) = 0.821 \cdot \log(A_{UPP}) + 1.210$ (13)	$\varepsilon_{rca} = 10.443 + 0.4556 \cdot A_{UPP} - 0.4936 \cdot ICS$ $R^2 = 81.64\,\%$ (14)
$\log(\varepsilon_{zsr}) = 1.017 \cdot \log(ICB) - 0.042$ $\cdot \log(H_{ca}) - 0.494 \cdot \log(H_{gr}) + 2.624$ (15)	$\varepsilon_{zsr} = 3.027 \cdot IDB^{1.037}$ $R^2 = 84.54\,\%$ (16)
$ICB = D_{60} - D_{90}$ (17)	$IDB = D_{30} - D_{60}$ (18)
To estimate the pavement's remaining service life, Eqs. (13) and (15) are employed, which yield reasonable results, unlike others that were assessed (19).	Through simple or multiple regression analysis, the prediction models in Eqs. (14) and (16) were developed for the in-service loads, based on parameters of the deflection basin (3).

Table V. Loads calculated by regression expressions

Transfer functions	**Correlation equation study**
$\varepsilon_{radm} = (0.856 \cdot Vb + 1.08) \cdot E_1^{-0.36} \cdot \left(\frac{N}{RF}\right)^{-0.2}$ (19)	$N_{8.2T\,adm} = 6.2064 \times 10^{13} \cdot ICS^{-3.3575}$ (20)
$\varepsilon_{zadm} = 0.021 \cdot N^{-0.25}$ (21)	$N_{8.2T\,adm} = 3.0310 \times 10^{15} \cdot IDB^{-4.3265}$ (22)
There are several transfer functions to estimate the admissible load values. In this study, 20 of them were tested, ten for fatigue control and ten for rutting. All of them yield different results: some are more permissible, and others are more restrictive. Finally, we decided to work with the Shell Transfer Functions (19) and (21) (20).	To indirectly estimate the remaining pavement life based on deflection basin parameters, this study generated Correlation Eqs. (20) and (22) between the ICS and IDB layer indices and the consulted transfer functions for fatigue and rutting control, respectively.

3. Indices for the structural condition and remaining service life of pavement

Pavement condition is estimated with the indices presented in Table VI.

4. Results

Fig. 1 presents the correlation results for the different models studied within the mechanistic and empirical approaches. In addition, it shows how the selected structural indices correlate (IVRF/IRVA *vs.* SCI) depending on the method taken as a reference.

Table VI. Indices for the condition and remaining service life of pavement

Pavement condition and remaining service life indices	**Remaining life ratio**
$SCI = \frac{SN_{eff}}{SN_{req}}$ (23)	Index for fatigue control $IVRF = \frac{\varepsilon_{radm}}{\varepsilon_{rca}} \circ \frac{N_{8.2T\,adm}}{N}$ (24) Index for rutting control $IVRA = \frac{\varepsilon_{zadm}}{\varepsilon_{zsr}} \circ \frac{N_{8.2T\,adm}}{N}$ (25)
The pavement's structural condition is evaluated based on the SNeff, determined using NDT from deflections obtained via FWD (South Africa method) and, in some methods, from pavement thickness (AASHTO 1993 and this work). This can be estimated using the structural condition index (SCI) proposed by the Texas Department of Transportation (TxDOT), as shown in Eq. (23) (21).	These indices, obtained using Eqs. (24) and (25), represent the remaining service life of the pavement, in a manner similar to the SCI. They are derived from the ratio between the permissible loads for the stress states or load repetitions, obtained from the transfer functions, vs. the in-service values, calculated from the pavement mechanics or the traffic study. They are the inverse of the deformation (εrca, εzsr) or loading stress consumption. The IVRF and IVRA indices, corresponding to Eqs. (24) and (25), represent ratios comparing allowable and actual in-service conditions, accounting for traffic variability through the estimated number of in-service load repetitions or through the representative loads used to calculate in-service strains. These indices integrate environmental factors, particularly their influence on layer moduli, which is crucial for these calculations. In standard applications, modeling long-term material property changes (aging) is often simplified, which may limit accuracy in capturing progressive pavement deterioration. While the index concept remains adaptable, its application across different pavement types requires specific structural models and appropriately calibrated transfer functions (ε_{adm}, N$_{adm}$) for those conditions, limiting direct extrapolation without such validation. Reliability considerations are generally embedded within the selected transfer functions or failure criteria.

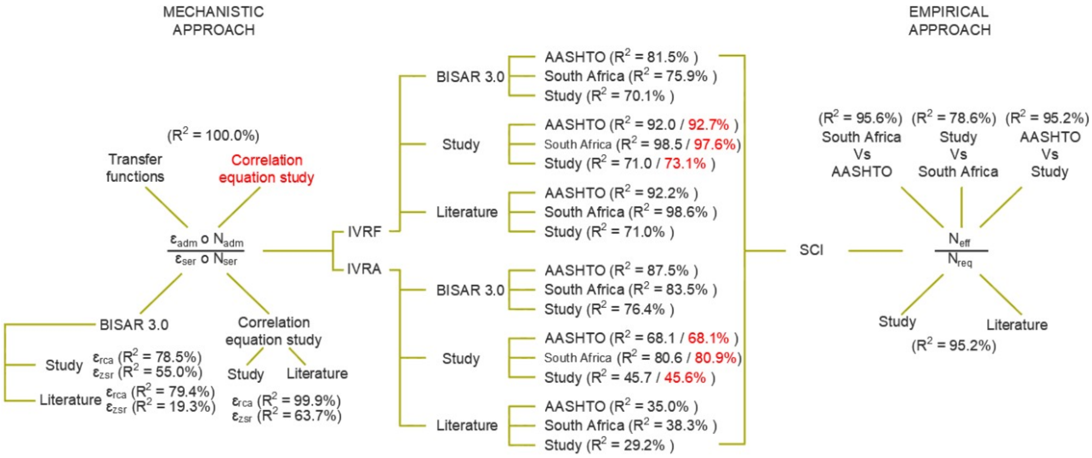

Figure 1. Coefficient of determination for the different models under study

Fig. 2 demonstrates how our model strongly predicts the radial tensile deformation at the base of the asphalt layer (R2=78.5 %). However, the fit is less accurate with the vertical compressive deformation in the subgrade, and the relationship between parameters is moderate (R2=55.0 %). A similar trend is observed in the literature-reported model and the control parameters for fatigue and rutting, with R2 values of 79.4 and 19.3 %. Both models, the one consulted and the one developed, predict the radial

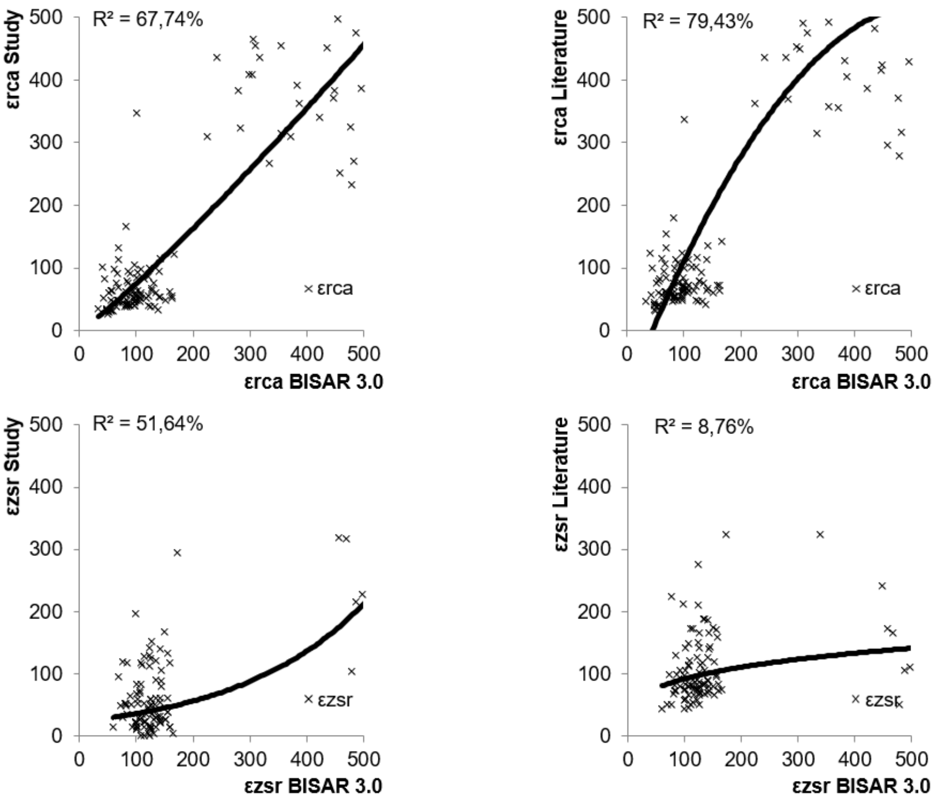

Figure 2. Relationship between εrca and εzsr in the studied models

deformation of the asphalt layer in the same way (R2=99.9 %). However, for the vertical deformation of the subgrade, the relationship is not as strong, and each model estimates the behavior of this parameter differently (R2=63.7 %) (Fig. 3).

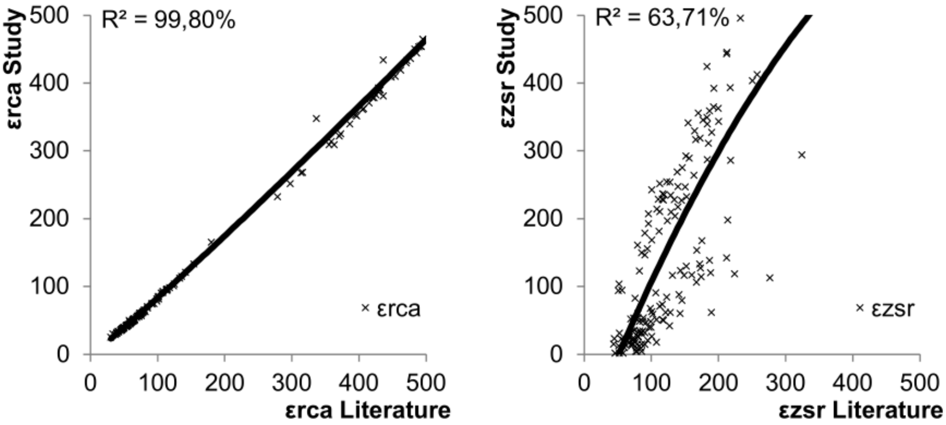

Figure 3. Relationship between εrca and εzsr, as determined in this study and the literature-reported model

To assess the structural capacity of the pavement, the AASHTO 93 method was used as reference due to its recognized international acceptance, extensive application, and proven reliability in the local context. As illustrated in Fig. 4, the AASHTO SNeff exhibits a strong relationship with the predictions obtained with the study's proposed methods and the South Africa approach, with R2 = 95,2 and 93,8 %, respectively. Similarly, a strong relationship is observed when determining the SNeff using our model and the South Africa method (R2=69.7 %).

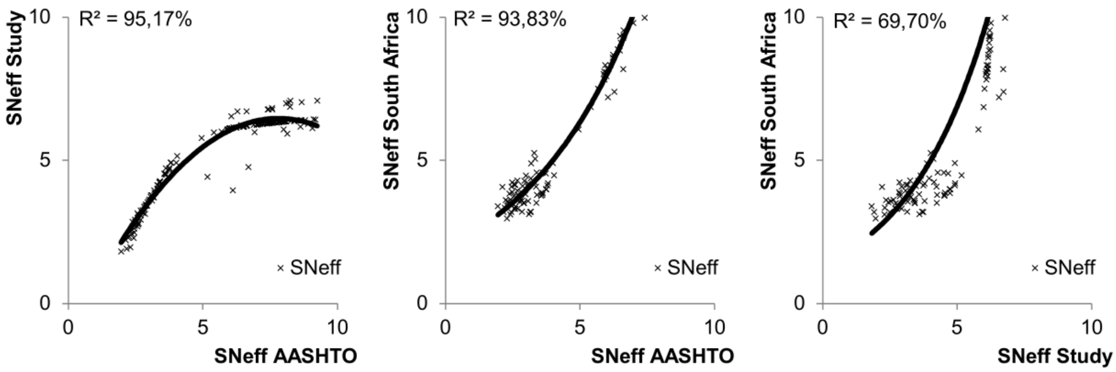

Figure 4. Relationship between the SNeff values determined through the different methods under study

To calculate the SCI, an expression was developed for determining the SNreq. The derived expression exhibits a strong correlation with an existing model in the literature (R2=95.2 %). Fig. 5 illustrates these relationships. Given the strong fit between our model, the literature-based model, and the general AASHTO equation, the SNreq parameter can be accurately predicted.

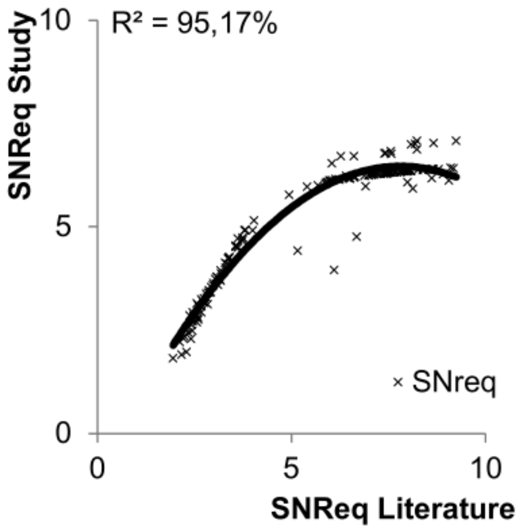

Figure 5. Relationship between the SNreq values determined using our model and the literature-reported approach

The methods selected as the foundation for this study are among the most rigorous in their calculations, particularly in estimating the remaining service life of pavement based on the relationship between the admissible loads (computed using transfer functions) and the service life (determined via BISAR 3,0). Additionally, as discussed above, the AASHTO 93 method was chosen as a reference framework due to its wide recognition, high acceptance, and extensive validation in the local context. As illustrated in Figs. 6 and 7 a strong correlation is observed between the structural conditions estimated for both the mechanistic and empirical approaches by means of the defined indices (IVRF/IVRA and SCI). These approaches consistently indicate whether pavement reinforcement is required, helping to identify structural deficiencies and mitigate pavement failure risks caused by fatigue and rutting due to repeated traffic loads.

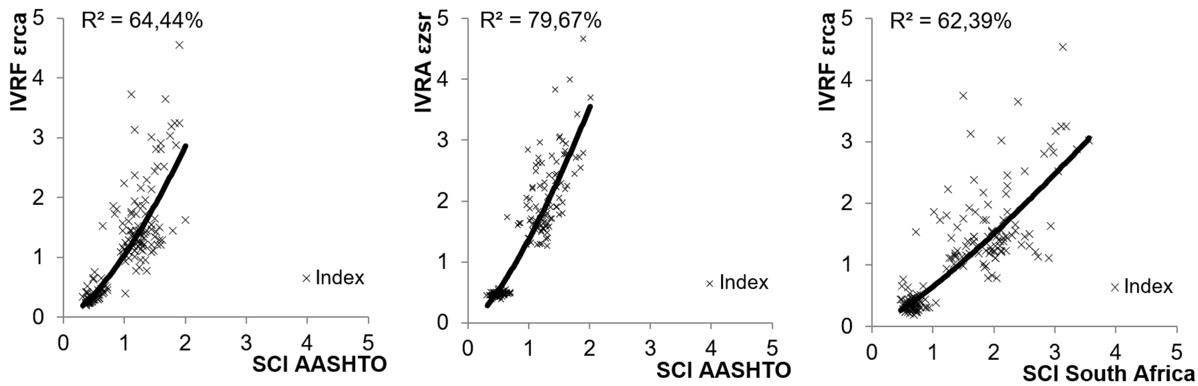

Figure 6. Relationship between IVRF (BISAR 3.0) and SCI, as determined through the methods under study

Similarly, Figs. 6 and 7 illustrate the SCI obtained with both models, showing a strong relationship with the IVRF/IVRA indices. This relationship is slightly stronger with the SCI obtained from the South Africa SNeff model. This behavior indicates that the structural condition of the pavement can be adequately predicted by applying any of the models.

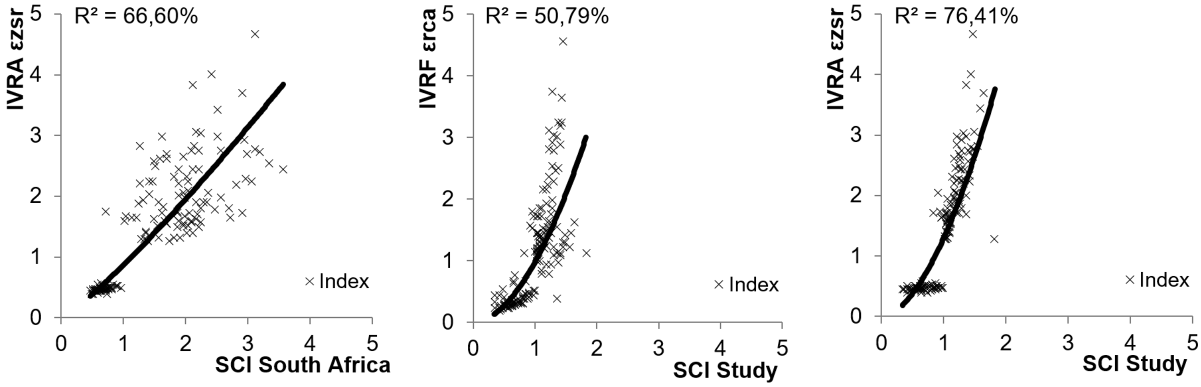

Figure 7. Relationship between IVRA (BISAR 3.0) and SCI, as determined through the methods under study

During this research, alternative methods were tested in which the structural condition is estimated exclusively based on deflection basin parameters, without relying on thickness values obtained from geotechnical or georadar exploration. These techniques include correlation equations to predict εrca and εzsr (mechanistic approach) and the South Africa method (empirical approach). As illustrated in Fig. 8, the relationship between SCI and IVRF in both methods is strong, confirming that a preliminary diagnosis of the pavement can be conducted by monitoring its structural condition and remaining service life. This eliminates the need for invasive testing, making these methods particularly useful for network-level pavement studies. Alternatively, this study proposes estimating the remaining service life by relating the permissible traffic loads (calculated based on the ICS and IDB layer indices) to the traffic study values. The correlation between the IVRF/IVRA and SCI determined through the AASHTO and South Africa methods indicates remarkable consistency. Fig. 9 illustrates the correlation results obtained with the South Africa method. The application of NDT methods can effectively aid in assessing pavement condition in terms of both structural capacity and remaining service life.

5. Discussion

In this study, the application of newly developed models for the structural assessment of pavement was tested while following the same approach and resolution principles as the techniques established in the literature. The results of the proposed expressions for evaluating structural parameters demonstrated strong alignment with findings from previously consulted methods, including correlation equations for predicting the radial tensile strain and the vertical compressive strain (mechanistic approach) as well as the structural number (empirical approach).

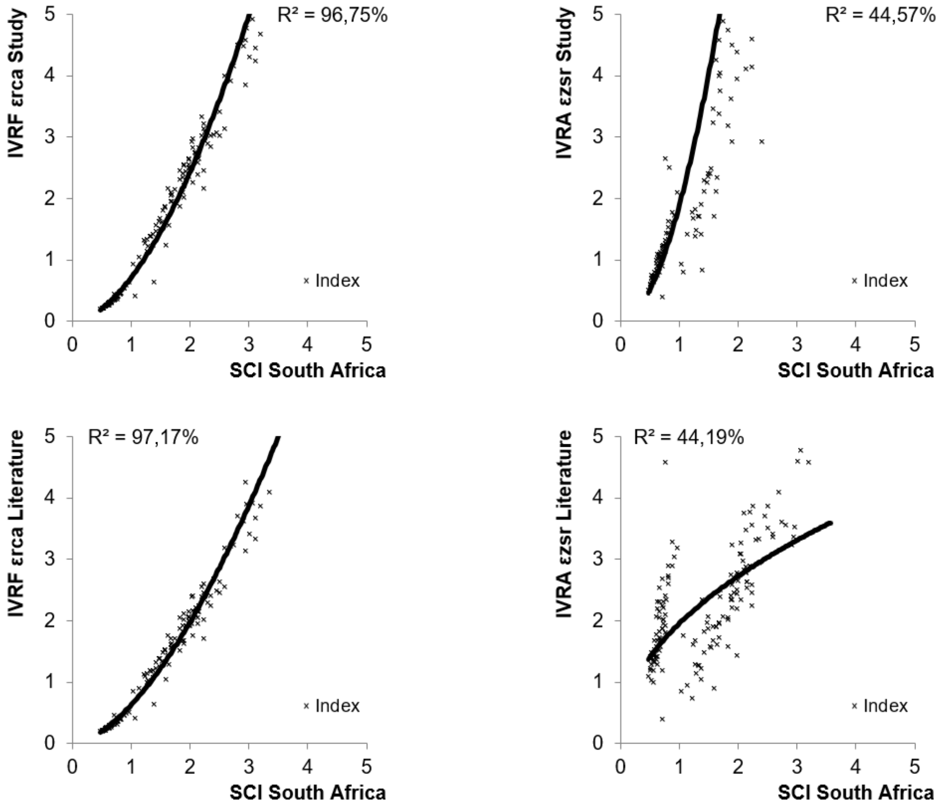

Figure 8. Relationship between IVRF/IVRA (correlation equations) and SCI, as determined with the South Africa method

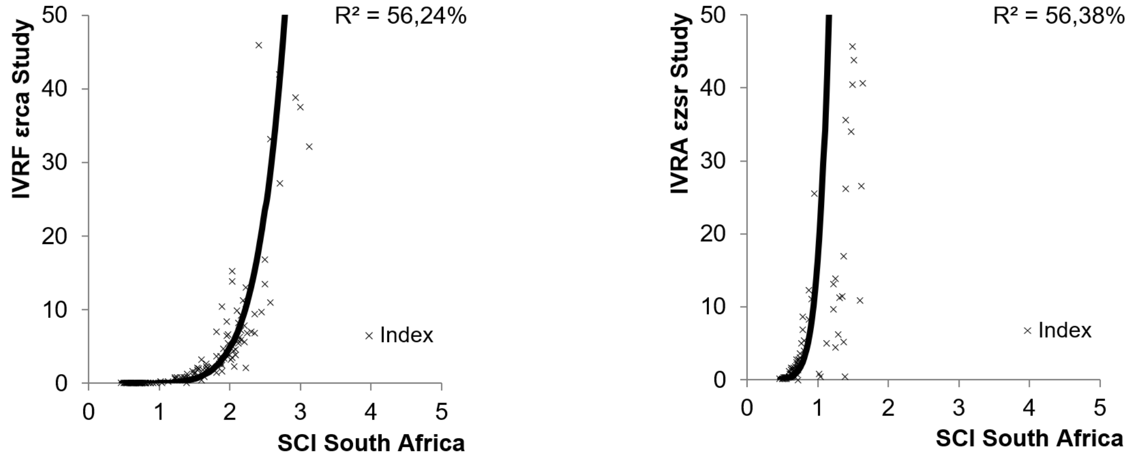

Figure 9. Relationship between IVRF/IVRA (traffic) and SCI, as determined using the South Africa method

In the specialized literature, (21) conducted a study on the structural condition index, concluding that it correlates strongly with the pavement's remaining service life as a function of fatigue and rutting.

This study successfully validated this relationship for the evaluated in-service pavement sections, which consisted of asphalt concrete wearing courses supported by untreated granular materials.

It is critical to note that these findings apply specifically to the flexible pavement structures evaluated in this study, *i.e.*, asphalt concrete layers over untreated granular materials, supported by various subgrade types. The formulations presented are based on traditional design methodologies developed under specific loading and environmental conditions. Therefore, direct application in significantly different contexts – such as varied climatic conditions, traffic loads, or pavement structures incorporating treated bases – requires careful consideration and likely adjustments through local calibration. This calibration should address structural layer coefficients, drainage coefficients, and reliability levels in order to ensure accurate predictions and facilitate adaptation to similar scenarios.

For network-level pavement assessments, the South Africa method is strongly recommended, as it demonstrates high accuracy in predicting the AASHTO SN. A key advantage of this method is its exclusive reliance on parameters derived from FWD deflection bowl measurements, thereby eliminating the need for thickness data. Unlike the current study, which developed models using theoretical structural frameworks, the South Africa method was formulated using field thickness data and FWD deflection bowl analyses. Consequently, a significant limitation of this study is the lack of model validation using real-world in-service pavement data.

There are several alternative, simple-to-use methods for estimating structural capacity and the remaining service life of pavement based solely on FWD data, without requiring thickness measurements. These approaches eliminate the costs and challenges associated with geotechnical exploration or georadar surveys while maintaining strong correlations with traditional rigorous methods typically applied at the project level. Furthermore, the indices employed in this study exhibit a good mutual correlation, thus supporting structural deficiency detection and collectively indicating whether reinforcement is required to meet structural and remaining life expectations.

6. Future research recommendations

For future studies, we recommend developing a model that exclusively relies on FWD-derived parameters, built upon detailed geotechnical and deflectometric data rather than on theoretical structural models, as was the case with this study. This new model should be designed to evaluate asphalt pavement structures with both treated and untreated granular layers.

7. Author contributions

Edwin Antonio Guzmán Suárez: conceptualization, methodology, software, formal analysis, data curation, writing (original draft)
Diego Fernando Gualdrón Alfonso: validation, formal analysis, writing (original draft)
Jorge Andrés Sarmiento Rojas: writing (review & editing), visualization, supervision

8. Conflict of interest

The authors declare that there are no conflicts of interest that could have influenced the research process or the interpretation of the results. This declaration is made in compliance with the standards of transparency and integrity in academic endeavors, ensuring that the study and its conclusions are based solely on objective data and analysis.

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