Development of Deflection Parameters to Evaluate the Structural Capacity of Flexible Pavements at the Network Level: Case Study for the State of Texas

Karthikeyan Loganathan[1], *Mayzan* Isied[1], *Ana Maria* Coca[2], *Mena* Souliman[1,*], *Stefan* Romanoschi[2], and *Samer* Dessouky[3]

[1]The University of Texas at Tyler, Tyler, Texas
[2]The University of Texas at Arlington, Arlington, Texas
[3]The University of Texas at San Antonio, San Antonio, TX 78249

Abstract. Pavement deflection has been used widely as a nondestructive technique to evaluate the structural capacity of pavements at both network and project levels. Various transportation agencies use several evaluation methods to evaluate the integrity of the pavement layers. Most of these up-to-date developed indices are exclusively based on either central deflections or one deflection point along FWD deflection bowl. However, no standardized method that utilizes the full FWD deflection bowl is available. This study aims to introduce new comprehensive pavement layer deflection and deflection bowl area parameters that are based on the entire FWD deflection bowl rather than one single deflection point and to relate the developed parameters to the field measured distress data. Thirty-five different pavement sections in the State of Texas were utilized in the study. Two comprehensive deflection parameters and a ranking scale were developed that may be utilized for the overall pavement structural condition evaluation.

1 Literature review

1.1 Deflection-based measurement devices

Pavement deflection has been widely utilized as a nondestructive technique to evaluate the structural capacity of pavement structures at both the network and project levels. Current devices include the Quest/Dynatest Rolling Weight Deflectometer (Quest/Dynatest RWD), Swedish Road Deflection Tester (Swedish RDT), Texas Rolling Dynamic Deflectometer (Texas RDD), Applied Research Associates, Inc. Rolling Wheel Deflectometer (ARA RWD), United Kingdom's Highway Agency Traffic Speed Deflectometer (UK TSD), and Falling Weight Deflectometer (FWD). The FWD employs a static testing method, which studies the impact resulting from a load falling from a certain height to closely simulate the effect of rolling traffic loads on the pavement surface. One of the most recent developments of traffic speed deflection measuring devices is the Danish Traffic Speed Deflectograph (TSD). The TSD uses a series of Laser sensors mounted on a stiff beam to measure the deflection of the pavement surface. However, the use of TSD is still limited and only a few countries are operating this system [1, 2].

The FWD is the main deflection-measuring device in the U.S. [3] that has been widely used as a reliable tool to measure pavement surface deflection bowl. With the development of multilayer elastic analysis software along with the development of accelerated test tracks, the measured deflection bowl was utilized to backcalculate layer moduli, and several parameters were derived to evaluate the structural condition of pavement structures. However, the backcalculation technique is not feasible to conduct at the network level due to its inability to produce a simple measure of the structural integrity of pavement and, therefore, its use is limited to project level evaluation.

1.2 Existing structural parameters

The structural adequacy index (SAI) was an early index developed by Haas et al. [4], which was calculated based on a single deflection value measured by the Benkelman beam test. Since the developed index depends on single deflection value, minor error during measurement could adversely affect the parameter. Scullion [5] introduced a new structural strength index to the pavement evaluation system (PES) used in Texas. Pavement conditions were rated in terms of visual distresses and present serviceability index. As a result of mechanistic approach in calculation of the index, deflection bowl parameters proved to be a more promising tool to estimate the remaining service life. However, the application of developed index was limited to project level.

Effective Structural Number (SN_{eff}) is considered to be a reliable parameter and many researchers have developed the SN_{eff} based on different approaches. Gedafa et al. [6] developed a SN_{eff} based on KDOT pavement management systems (PMS) data. Multiple regression models for SN_{eff} were developed for twelve

* Corresponding author: msouliman@uttyler.edu

different road categories utilized in the state of Kansas. Developed models were successfully correlated to the SN_{eff} calculated based on AASHTO 1993 procedure. The models were developed based on various independent variables such as pavement mid-depth temperature and subgrade modulus. Calculation of all required variables included in regression models could be difficult for pavement engineers to implement.

Elbagalati et al. [7] developed a model to predict pavement structural capacity at an interval of 0.16 km (0.1 mi.) based on the RWD measurements. Structural Condition Index (SCI) was developed by dividing SN_{eff} by Required Structural Number (SN_{req}). The results showed that the SCI was very sensitive to the pavement deterioration, based on a sensitivity analysis conducted on the TxDOT PMS data. Though samples that were predicted to be structurally-deficient suffered from asphalt stripping and material deterioration problems, few sections were in very good condition according to PCI values.

Saleh [8-10] simplified the approach for structural capacity evaluation of flexible pavements at the network level by introducing some parameters such as Normalized Area Ratio Parameter under Area Ratio Concept. However, those parameters were based only on portion of the deflection bowl.

Pavement curvature is another parameter that is widely used in Australia and is defined as the difference between the central deflection and the deflection measured at 200 mm from the center of the load [11]. Based on the collected literature, it can be concluded that throughout the last several decades, researchers have developed parameters to assess the structural integrity of the pavement system from the deflection bowl measurements. Although various transportation agencies have used several methods, there is no standard acceptable method available to provide accurate estimates of the structural integrities of pavement layers and the subgrade. Also, none of the previously developed deflection parameters had utilized the full deflection bowl.

2 Objectives

Since most of the up-to-date developed indices are exclusively based on either central deflection or one deflection point along FWD deflection bowl. Also, since that there is no comprehensive deflection or structural index available that utilizes the entire FWD deflection bowl area, therefore; the proposed research study aims to achieve the following objectives:

- Introduce new comprehensive pavement layer deflection and deflection bowl area parameters which are based on the entire FWD deflection bowl rather than one single deflection point.
- Relate the developed deflection and deflection area parameters to field measured distresses, particularly, fatigue measured area (%).
- Develop a scoring system to rank the strength of the pavement sections based on the available FWD testing data and the newly developed deflection parameters.

3 Deflection and pavement condition data extraction

Data related to the 35 LTPP pavement sections considered for the study and the FWD deflection measurements were collected from the Pavement Monitoring (MON) module in the LTPP database. FWD measurements and their corresponding deflection data were stored in tables with MON_DEFL as a part of their names. The extracted data included 1) Peak drop load, 2) Drop height, 3) Sensors offset distances from the load point, and 4) Peak deflection values recorded by each sensor.

Structural distresses such as fatigue cracking and rutting were measured in m^2 and mm, respectively. Functional distress such as International Roughness Index (IRI) was measured in m/km. The measurements of both structural and functional distresses were conducted based on the LTPP Distress Identification Manual [12]. The distress data were extracted from the performance tab for each section at the corresponding FWD measured date.

4 Development of comprehensive deflection parameters

4.1 Comprehensive area ratio (CA_r)

The comprehensive area ratio (CA_r) was developed based on different deflections measured by different sensors from the center of the load plate. Deflections are considered at intervals similar to FWD testing machine sensors locations (D_0, D_{203}, D_{305}, D_{457}, D_{610}, D_{914}, and D_{1524}). Comprehensive Area under Pavement Profile (CAPP) is generally the total area of normalized deflection bowl throughout the entire 1524 mm bowl length. For a strong pavement section, deflections measured at different sensor offsets would differ in minimum magnitude compared to the D_0. An imaginary rigid section is assumed, which would have constant deflection throughout the length (i.e., $D_0 = D_{203} = D_{305} = \ldots = D_{1524}$) of deflection bowl. The CAPP of an imaginary rigid pavement section having a single unit deflection is equal to 1524 mm^2/mm, and for any rigid pavement section deflection bowl may be calculated as:

$$CAPP = \left(\frac{1}{D0}\right) * \{203*\left(\frac{D0+D203}{2}\right) + 102*\left(\frac{D203+D305}{2}\right) + 152*\left(\frac{D305+D457}{2}\right) + 153*\left(\frac{D457+D610}{2}\right) + 304*\left(\frac{D610+D914}{2}\right) + 610*\left(\frac{D914+D1524}{2}\right)\} \tag{1}$$

When the calculated CAPP for a pavement section is divided by the CAPP of imaginary rigid pavement section, the result would be the portion of considered pavement section in the imaginary rigid section profile, which is CA_r. A strong pavement section would cover more area than a weak pavement section and hence CA_r would be higher for a strong section and comparatively less for a weak section. For an extremely stiff pavement section, the CA_r value could be nearly 1.0 while a weak section could have a CA_r value of 0.1.

$$CA_r = \left(\frac{1}{1524*D0}\right) * \{203*\left(\frac{D0+D203}{2}\right) + 102*\left(\frac{D203+D305}{2}\right) + 152*\left(\frac{D305+D457}{2}\right) + 153*\left(\frac{D457+D610}{2}\right) + 304*\left(\frac{D610+D914}{2}\right) + 610*\left(\frac{D914+D1524}{2}\right)\} \quad (2)$$

where D_0 is the center deflection, D_{1524} is the deflection at offset 1524 mm from the load and D_i is the deflection at offset i (mm) from the load.

Two pavement sections (SHRP: 1093 and 3729) with different properties were compared as shown in Figure 1. By observing the figure, area covered by the SHRP section 3729 pavement profile is more than half the area of imaginary rigid pavement whereas the SHRP section 1093 covers comparatively lesser area of imaginary rigid pavement section. As expected, the CA_r for SHRP section 3729 is 0.7 whereas 0.4 for SHRP section 1093.

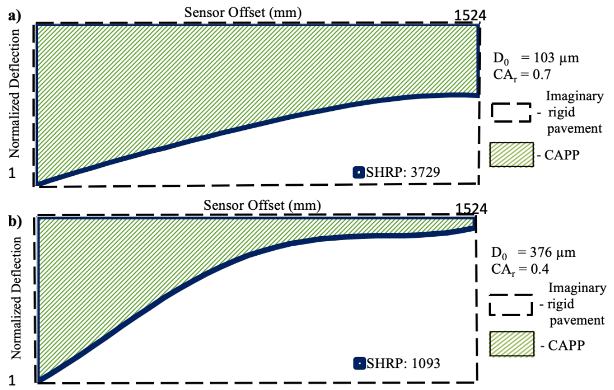


Fig. 1. Normalized area of deflection profiles for SHRP sections: (a) 3729 and (b) 1093.

4.2 Normalized comprehensive area ratio (CA_r')

The response of structural layers of pavement differ for different loading conditions or targeted load levels. However, the parameter CA_r was not capable of accounting the change in response by pavement section to differing target load levels, as shown in Figure 2. The calculated CA_r for the SHRP section 1049 was 0.5 for all four targeted load levels irrespective of the change in central deflection due to the increase in loads. In addition, it is known that the area ratio parameter account only for the structural capacity of pavement sections above subgrade. The concept of normalized area ratio was then introduced in order to overcome the limitation associated with the area ratio parameter, CA_r.

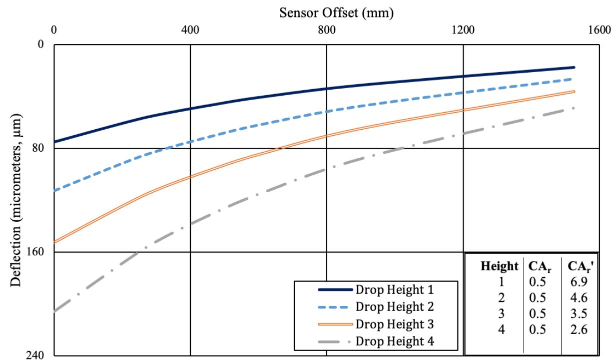


Fig. 2. Illustration on importance of CA_r' based on SHRP section 1049.

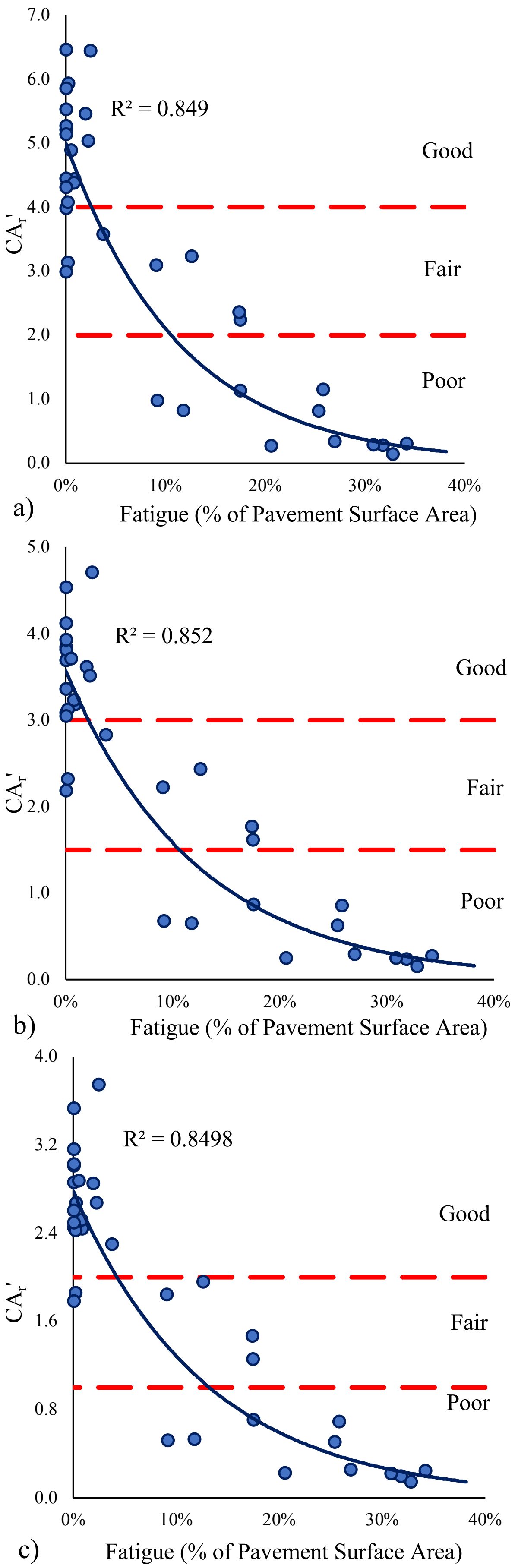
By combining the area ratio and central deflection into a single parameter could account for the structural property of the entire pavement section (both subgrade and layers on top of subgrade). Therefore, the area parameter is normalized by dividing the CA_r by D_0, and the new parameter was termed as Normalized Comprehensive Area Ratio (CA_r').

$$CA_r' = \left(\frac{1}{1524*D0*D0}\right) * \{203*\left(\frac{D0+D203}{2}\right) + 102*\left(\frac{D203+D305}{2}\right) + 152*\left(\frac{D305+D457}{2}\right) + 153*\left(\frac{D457+D610}{2}\right) + 304*\left(\frac{D610+D914}{2}\right) + 610*\left(\frac{D914+D1524}{2}\right)\} \quad (3)$$

where D_0 is the center deflection, D_{1524} is the deflection at offset 1524 mm from the load and D_i is the deflection at offset i (mm) from the load.

5 Development of a multi-scale to categorize pavement sections

The Comprehensive Area Ratio (CA_r') was correlated to the physical distress data, in particular, fatigue measured during FWD field tests (similar to FWD test date) as shown in Figure 3. Fatigue failure is considered one of the important distresses in a pavement section, which would lead to serious issues resulting in reconstruction of a pavement structure, therefore; it may be used as a base to rank the pavement sections from good to poor. Fatigue cracking is measured in terms of area on surface of a pavement section and was changed to a percentage by dividing the measured fatigue area to the known LTPP section area. Structurally good pavement section must possess lesser area of fatigue cracking compared to a structurally poor pavement section.



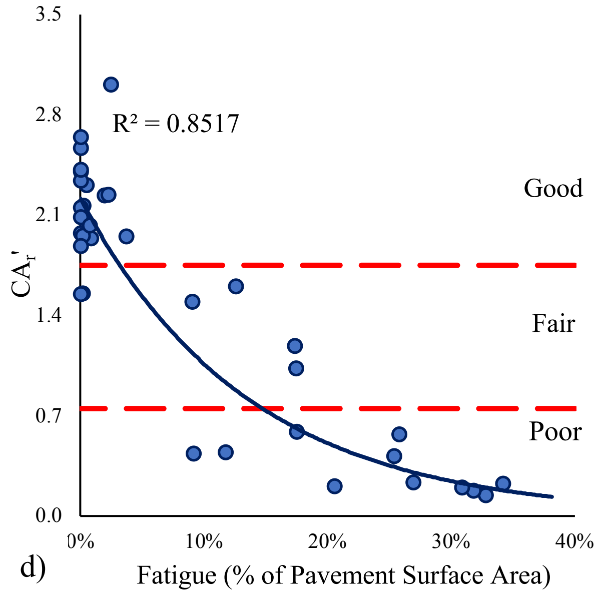


Fig. 3. Development of CA_r' scale to rank pavement sections based on fatigue: (a) drop height 1, (b) drop height 2, (c) drop height 3, and (d) drop height 4.

The relationship between fatigue and developed parameter CA_r' was found to be sensible and reliable with coefficient of determination (R^2) greater than 0.8. As expected, pavement sections with lesser fatigue area exhibits higher CA_r' whereas sections with higher fatigue area exhibits lesser CA_r', which proves the ability of the developed parameter to assess pavement sections. Based on the illustration (Figure 3), a scale was developed to categorize structurally good, fair, and poor pavement sections. The scale was developed based on individual drop load levels, which can be employed to any pavement section that has the maximum probable traffic load matching the target load level.

Developed scoring scale is shown in Table 1. For a typical Equivalent Single Axle Load (ESAL), design load considered during pavement design is 18 kips (18*103 lbs.). Required CA_r' scale for network level pavement sections (interstates and highways) is >3 for good, between 1.5 to 3 for fair, and <1.5 for poor as shown in Table 1.

Table 1. Developed range of scale for CA_r'.

Normalized Comprehensive Area Ratio, CA_r' ranges			
Target Load	**Pavement structural capacity ranking**		
	Good	**Fair**	**Poor**
27 kN (6,000 lbs)	> 4.0	2.0 - 4.0	< 2.0
40 kN (9,000 lbs)	> 3.0	1.5 - 3.0	< 1.5
53 kN (12,000 lbs)	> 2.0	1.0 - 2.0	< 1.0
71 kN (16,000 lbs)	> 1.8	0.8 - 1.8	< 0.8

5 Conclusions

There are few simple procedures employed by agencies to identify structurally weak pavement sections based on FWD data, none of them utilizing the full deflection bowl. New comprehensive deflection parameters were developed in this study utilizing the extracted data for 35 LTPP pavement sections in the State of Texas. All of the newly developed parameters were based on the entire extent of the deflection bowl to overcome the limitations in the previously developed parameters, and to produce more robust parameters capable in capturing the pavement structural conditions of the entire pavement structure.

The concept of normalization was introduced so that the area ratio parameter would reflect the response of pavement structures to traffic load variations (four different FWD drops load levels). Based on the observed acceptable correlation between normalized comprehensive area ratio (CA_r') and pavement distress data, a multi-scale was developed to represent four load levels. In addition, same scale may be utilized for a typical Equivalent Single Axle Load (ESAL) evaluation at target load of 40 kN (9,000 lbs).

CA_r' can be considered as a simple and robust parameter to evaluate the structural capacity of a pavement section at the network level. The developed parameter, CA_r', would assist the state DOTs and local highway agency officials to make more informed decisions related to the most suitable maintenance and rehabilitation strategies. However, field validation of developed parameters is recommended to be implemented into the PMS databases of transportation agencies.

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