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**A Mechanistic Empirical Approach for the Evaluation of the Structural Capacity and
Remaining Service life of Flexible Pavements at the Network Level**

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ABSTRACT: Road asset managers need to utilize reliable indicators for the structural condition and remaining service life at the network level to make rational decisions of the required funding and the optimum strategies for maintenance and rehabilitation. The surface deflection bowls and pavement critical responses were generated by computer simulations for a total of 2880 flexible pavement sections. The normalized area was computed from the deflection bowl data and it was found to be very well correlated with the compressive strain at the top of the subgrade. While the pavement surface curvature and area under pavement profile were highly correlated with the tensile strain at the bottom of the asphalt concrete layer. Thus, these parameters were used to evaluate the remaining service life in rutting and fatigue. Field data showed an excellent match between the trends obtained from the field and computer simulated data.

KEYWORDS: Deflection, FWD, Curvature, Normalized Area Ratio, Remaining Service Life

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BACKGROUND

Most of the current pavement management systems rely on pavement distress surveys and road roughness to come up with combined indices to rank the structural condition of pavement sections. However, in many instances, pavement distress surveys and roughness indices alone can provide misleading information about the actual structural condition of the pavement. For example, a pavement with shallow rutting and moderate to severe fatigue cracking can be resurfaced with thin asphalt overlay and based on the pavement distress survey and roughness; this pavement would be incorrectly ranked as a structurally sound pavement. While in fact the pavement is still structurally poor and the thin surface asphalt layer will only last a very limited short time before it will deteriorate. Zhang reported that huge quantities of bituminous mix in the form of seal coats and thin hot mix asphalt overlays are applied by the TxDOT every year to improve ride quality and seal existing cracks, but these measures do not correct possible underlying weaknesses that will cause roughness or distress to quickly reappear (Zhang et al. 2003). Thus, although distress condition indices can provide some indications of the pavement structural capacity, they alone are not sufficiently accurate indicators of pavement structural condition (Murphy 1998). Therefore, in order to have sound allocations of funding and better maintenance and rehabilitation strategies, pavement evaluations must be based on both the pavement distress surveys and an improved network level structural condition evaluation.

Pavement deflection has been widely used as a nondestructive technique to evaluate the structural capacity of pavements at both the network and project levels. Several devices have been used to measure field deflections by highway agencies (Coetzee et al. 1989). The Falling weight deflectometer, FWD, is one of the most reliable and commonly used devices to measure pavement surface deflections. The FWD device applies an impact load falling from certain

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height over a segmented plate and the deflections at the center of the load and at offsets commonly 300 mm apart (12 inches) from each other are measured through a set of geophones. The FWD closely simulates the effect of rolling traffic loads on the pavement surface. However, one major disadvantage of the FWD is that the device needs traffic control as it moves and stops frequently, thus it does not move at the same speed of traffic. Consequently, the use of FWD to measure the pavement surface deflections at the network level will be significantly expensive and impractical. This has led to the development of other devices that can travel at the speed of traffic (Rada 2009; Rada et al. 2010). 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 (Ferne et al. 2009). However, the use of TSD is still limited and only few countries are operating this system parallel to the FWD to correlate the deflection measured from both devices and gain more understanding of the new system. Once the TSD and similar systems become widely available, the measurements of the surface deflection at the network level on a regular basis will become affordable and practical.

Researchers have developed several approaches to analyze deflection data to evaluate the structural condition of the pavement. Backcalculation of pavement layer moduli and deflection bowl parameters were commonly used to evaluate the structural condition of the pavement structure. Backcalculations of layers moduli require the pavement layer thicknesses to be known, however, most of the highway agencies do not record layer thicknesses at the network level. In addition, backcalculations will require intensive amount of time and calculations effort at the network level. Thus, backcalculation technique is not feasible to be carried out at the network level and it is only more suitable for project level evaluation.

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Deflection basin parameters (DBPs), derived from the deflection bowl, have been used for pavement condition assessment (Lee 1997). Several researchers have developed relationships between deflection basin parameters and pavement responses such as stresses and strains.

The maximum central deflection was found by many researchers to be more related to the entire pavement structure and it also reflects the condition of the subgrade. High central deflection is usually associated with weak subgrade. The difference between the central deflection and the deflection at an offset of 300 mm from the center of the load ($D_0 - D_{300}$) is called by some researchers base layer index (BLI) or also called the surface curvature index SCI and is more related with the surface and base condition (Horak and Emery 2006, Kim and Park 2002). The parameter ($D_{300} - D_{600}$) is called middle layer index (MLI) or also called the base damage index (BDI) and it is more related to the subbase layer (Horak and Emery 2006; Kim and Park 2002). Whereas, the ($D_{600} - D_{900}$) is designated as the lower layer index (LLI) or base curvature index (BCI) and it reflects the condition of the subgrade (Horak and Emery 2006; Kim and Park 2002). There are many other parameters that were derived from the deflection bowl such as area parameter which is the total area of the deflection bowl normalized by the central deflection and this parameter is highly correlated with the pavement stiffness. Stiff pavements display a large area parameter, while weak pavement structures display a small area parameter (Hoffman and Thompson 1981). 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 ($D_0 - D_{200}$). Pavement curvature is used to predict the tensile strains under the asphalt concrete layer and therefore the fatigue life of asphalt surface layer.

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Deflection ratio is also one of the most commonly used parameters by some highway agencies in Australia. Deflection ratio is defined as the ratio between the measured deflections at 250 mm offset from the center of the load to the maximum central deflection. The Department of Transport and Main Roads (DTMR) in Queensland, Australia, uses the deflection ratio parameter to evaluate pavement structural capacity. The higher the deflection ratio, the stiffer and stronger is the pavement structure (DTMR 2012). The research carried out by the author has found that the deflection ratio is not sensitive to the subgrade condition and it only provides assessment of the pavement structure above the subgrade as it will be discussed in the later sections of the paper.

The Texas Transportation Institute has developed the statistical Structural Strength Index (SSI) (Scullion 1988). The SSI was developed based on the Surface Curvature Index (SCI) and the Falling Weight Deflectometer (FWD) deflection of the farthest sensor, which is 1829 mm (72 inches) away from the center of the applied FWD loading. However, recent studies by TxDOT indicated that the SSI was not effective enough to discriminate between pavements that need structural reinforcement from those that do not, therefore, Zhang and his co-authors concluded that the SSI cannot be effectively used at the network level to identify pavement sections with structural deficiencies and they also added that the SSI does not relate the FWD values to the structural capacity indicators, such as the Structural Number (SN), that are used for pavement design (Zhang et al. 2003). Romanoschi and Metcalf (1999) proposed a method that gives a direct regression relationship between the measured FWD deflection and the structural strength of the pavement, expressed as the pavement's Structural Number. The Structural Number (SN) regression equations were expressed separately for pavement structures having granular base and subbase layers, and for pavement structures having a stabilized base layer.

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In this research paper, computer simulations for 2880 flexible pavement sections were carried out to generate deflection bowls under FWD loading of 40 kN (9000 lbs) and a contact stress of 565.88 kPa (82 psi). The same pavement sections were subjected to deflectograph loading which is equivalent to the standard axle load of 80 kN (18000 lbs) and tire pressure 750 kPa (108.8 psi). The area ratio, normalized area ratio, surface curvature and area under pavement surface profile parameters derived from the FWD simulations were correlated with the pavement response under the standard axle load. The actual FWD field tests data were used to verify the accuracy of the computer simulations.

AREA PARAMETER AND AREA RATIO CONCEPT

Area parameter (AREA) is defined as the area of one side of the deflection bowl between offset 0 mm (directly under the center of the load) and 900 mm divided by the central deflection D_0 . The Area parameter derived from the FWD deflection bowl was initially proposed by Hoffman and Thompson (10), see Equation 1.

$$AREA = \frac{50}{D_0} \left\{ \left(\frac{D_0 + D_{900}}{2} \right) + \sum_{i=50}^{850} D_i \right\} \quad \text{Equation (1)}$$

D_0 = Central deflection at offset 0

D_{900} = The deflection at offset 900 mm from the load

D_i = Deflection at offset distance i in (mm) from the load

For a very stiff strong pavement structure, it can be assumed that all the sensor deflections are almost equal, thus the area parameter tends to reach the upper limit of 900 mm²/mm. This would

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indicate an extremely stiff pavement structure regardless of the subgrade condition. In this case the deflection bowl will be a rectangle of depth D_0 mm and width of 900 mm

$$D_0 = D_{50} = D_{100} = \dots \dots D_{900}$$

$$AREA = \frac{D_o * 900}{D_o} = 900 mm^2 / mm$$

Area Ratio Concept

The area ratio parameter which is none dimensional parameter and is defined as the ratio between the area parameter of any pavement structure to the area parameter of the stiffest pavement was proposed by Saleh (Saleh 2014; 2015; 2015). The area ratio parameter is a parameter that theoretically ranges from 0 to 1, while in the practical sense; it ranges from 0.3 for very weak structures to slightly less than 1 for stiff pavement structures (Saleh 2014; 2015). Therefore, for a 900 mm length of deflection bowl, the area ratio parameter can be defined by Equation 2.

$$A_r = \frac{50}{900 * D_0} \left\{ \left(\frac{D_0 + D_{900}}{2} \right) + \sum_{i=50}^{850} D_i \right\} \quad \text{Equation (2)}$$

A_r = Area ratio parameter

D_0 = Maximum Central Deflection

D_{900} = Surface deflection at offset 900 mm

D_i = Surface deflection at offset (i) mm.

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Area and Deflection Ratios versus Subgrade Stiffness

In order to understand the sensitivity of the deflection ratio and area ratio to subgrade stiffness, two similar pavement structures constructed over two different subgrades were subjected to falling weight deflectometer simulations. Pavement sections in Figures 1a and 1b are two similar strong flexible pavement structures; pavement 1a is constructed over weak subgrade with resilient modulus 30 MPa (4351 psi) while pavement section 1b is constructed over strong subgrade with resilient modulus 100 MPa (14504 psi). Circly multilayer system software was used to simulate FWD, (Wardle 2012). In the multilayer analysis by Circly, the base course materials and the subgrade were modelled as cross anisotropic materials with the cross anisotropic ratio of 0.5 as recommend by the Australian guidelines (Austroads 2012). The anisotropic ratio is defined by equation 3.

$$\text{Cross anisotropic ratio} = \frac{E_h}{E_v} \quad \text{Equation 3}$$

Where

E_h = The horizontal resilient modulus

E_v = Vertical resilient modulus

In addition the basecourse materials were sublayered according to the Austroads (2012) guidelines to account for the nonlinear behavior of the granular materials.

Table 1, shows the computed surface deflections at 50 mm intervals and the deflection ratio, area ratio and normalized area ratio for both pavement sections. From Table 1, it can be noted that the deflection ratio and area ratio parameters are not sensitive to subgrade condition and in fact both

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parameters provided misleading evaluation. The deflection ratio for strong pavement over weak subgrade is computed as 0.92 while for the same strong pavement over strong subgrade, the deflection ratio value is calculated as 0.85 which gives false indication that the structural condition of pavement 1a is better than the structural condition of pavement 1b; while this is not true. The same problem exists with the area ratio parameter. Therefore, it can be concluded that both the deflection ratio and area ratio are not sensitive to subgrade condition and they cannot be used to make an overall evaluation of the entire pavement structure. The area ratio and deflection ratio can however provide reasonable evaluation of the pavement structure above the subgrade.

Figure 1a

Figure 1b

Table 1

Normalized Area Ratio

To overcome the limitation of the area ratio, and to account for the effect of the subgrade condition, the normalized area ratio given by equation 4 was proposed by Saleh (2014; 2015; 2015). Equation 4 gives the value of the normalized area ratio from the deflection values between offset 0 to 900 mm from the center of the load.

$$A_r' = \frac{50}{900 * D_0^2} \left\{ \left(\frac{D_0 + D_{900}}{2} \right) + \sum_{i=50}^{850} D_i \right\} \quad \text{Equation (4)}$$

From Table 1, it can be seen that the normalized area ratio (A_r') for strong pavement over strong subgrade for pavement section 1b is 3.06 which is considerably larger than the normalized area

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ratio for pavement section 1a which is 1.64. The effect of the subgrade condition makes remarkable difference in the value of the normalized area ratio of the two pavements 1a and 1b.

Figures 2a and 2b show the relationship between the normalized area ratio and normalized deflection ratio determined from the deflection bowls generated from Circly analysis for 2880 pavement sections. A linear relationship was found between the normalized area ratio and the normalized deflection ratio with a very strong correlation ($R^2=0.9914$). Figures 2c and 2d show a similar trend of the actual FWD field data carried out on two flexible pavements in Queensland, Australia. The flexible pavement in Figure 2c consists of asphalt concrete layer over granular base course and the flexible pavement in Figure 2d consists of asphalt concrete layer over cement treated base. It is clear that the computer simulated data and actual FWD measured data show a similar range of A_r' for flexible pavements of asphalt over granular materials (0.25 to 3.5) and also for flexible pavements with cement treated bases (CTB) in which the range of the normalized area ratio is from 0.5 up to 7.0 depending on the moduli of the CTB and its thicknesses.

Figure 2a

Figure 2b

Figure 2c

Figure 2d

Saleh develop a multiscale criteria that can be used to classify the structural capacity for four different flexible pavement compositions namely as shown in Figures 3a to 3d: flexible pavement with granular base course and asphalt concrete layer of thickness 100 mm or larger,

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flexible pavements with granular base and surface treatments, flexible pavements with granular base course and thin asphalt concrete layer of 50 mm thickness or less and flexible pavements with cement stabilized base course and asphalt concrete layer of 100 mm or larger (Saleh 2014; 2015).

Sensitivity of the Normalized Area Ratio to Pavement Nonlinearity

In order to examine the sensitivity of the normalized area ratio to the pavement response, the falling weight deflectometer test was carried out on several pavement sections in Queensland, Australia, at multiple load levels 40 kN, 60 kN, 80 kN and 100 kN (8992.358, 13488, 17984.72, 22480.89 lbs). The FWD test was carried out at different lateral locations to capture the loaded and unloaded areas of the highway pavement cross sections. Some sections showed obvious nonlinear behavior as shown in Figure 3a. Figures 3a and 3b show the relationship between the FWD load and the central deflection and the normalized area ratio. It is clear that the normalized area ratio is sensitive to the applied load and pavement response. In Figure 3a, the deflection and applied load are following nonlinear behavior and the normalized area ratio showed the same behavior. In Figure 3b, the applied load and the central deflection followed a linear relationship and the normalized area ratio followed the same trend. The author analyzed several hundreds of FWD tests and in all analyzed data the normalized area ratio was quite sensitive to the applied loads and pavement response. This clearly indicates that the normalized area ratio can capture the pavement response under different loadings and different levels of stresses.

Figure 3a

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Figure 3b

Maximum Compressive Strain at the Top of the Subgrade

In the previous section, it was demonstrated that the normalized area ratio is sensitive to the subgrade condition. In order to further examine this hypothesis and to further examine the relationship between the normalized area ratio and the pavement responses, computer simulations using Circly for 2880 flexible pavement sections with different thicknesses and stiffness properties were carried out. The relationship between the normalized area ratios computed based on the FWD loading was correlated to the pavement response under the standard axle 80 kN load for the same pavement sections. The normalized area ratio was very well correlated to the compressive strain at the top of the subgrade with a coefficient of determination $R^2=0.905$ as shown in Figure 4a and Equation 5.

$$\varepsilon_{zz} = 4 * 10^{-4} * Ar^{1-1.111} \quad \text{Equation 5}$$

$$R^2 = 0.9047$$

The strong correlation between the normalized area ratio and the compressive strain at the top of the subgrade supports the hypothesis that the normalized area ratio provides strong correlations with the overall pavement stiffness and therefore the overall structural capacity of the pavement. It is also indication that the normalized area ratio can provide strong correlation with pavement permanent deformation which is usually correlated to the compressive strain on the top of the subgrade.

The central deflection was also used by many agencies as a good indication of the overall pavement structural capacity and also as a good indication of the subgrade condition. Therefore,

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it was expected that the central deflection will be strongly correlated to the normalized area ratio. Figure 4b shows the relationship between the central deflection, D_o (mm) and the normalized area ratio generated from the Circly computer simulations for the 2880 flexible pavement sections. Figure 4b shows that the central deflection and the normalized area ratio are very well correlated with R^2 value of 0.92. Figures 4c and 4d show the relationship between the maximum central deflection, D_o (mm), and the normalized area ratio based on actual FWD field data measurements carried out on 1964, and 1916 flexible pavement sections in Queensland, Australia. The relationship between the central deflection and normalized area ratio based on the computer simulation in Figure 4b and that based on actual FWD field measurements are closely matching each other.

Figure 4 a

Figure 4b

Figure 4 c

Figure 4d

Tensile strain at the bottom of Asphalt Concrete Layer

Bottom up fatigue of asphalt concrete layer is directly related to the tensile strain at the bottom of the asphalt concrete. By analyzing the Circly computer simulations for the 2880 pavement sections, it was found that, the tensile strain at the bottom of asphalt due the standard axle load is well correlated with the pavement surface curvature parameter computed based on the FWD loading simulations. The pavement curvature is defined as shown in Equation 6:

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$$\delta = D_0 - D_{200} \quad \text{Equation 6}$$

δ = Pavement surface curvature (mm)

D_0 = maximum central deflection (mm)

D_{200} = Deflection at 200 mm offset from the center of the load

Figure 5a and Equation 7 show the relationship between the maximum tensile strain at the bottom of the asphalt concrete layer under the effect of the standard axle load of 80 kN and the surface curvature calculated based on the FWD using Circly computer simulations.

Figure 5a

$$\begin{aligned} \varepsilon_t &= 2.3 * 10^{-3} * \delta + 2 * 10^{-5} \\ R^2 &= 0.964 \end{aligned} \quad \text{Equation 7}$$

ε_t = is the maximum tensile strain at the bottom of the asphalt concrete layer

$\delta=(D_0-D_{200})$ =Surface curvature parameter in mm

It is obvious from Figure 5a that the curvature parameter is highly correlated with the tensile strain at the bottom of the asphalt concrete layer and therefore can be used to predict the fatigue performance of the asphalt concrete layer.

Thompson (1989) and Thompson and Elliot (1985) have proposed the Area Under the Pavement Profile (AUPP) as another promising parameter for the determination of the tensile strain at the bottom of the asphalt concrete layer . Garg and Thompson (1998) have concluded in a study for Mn/Road test sections that the AUPP is an important deflection basin parameter that can be used

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to predict the tensile strain at the bottom of the AC layer quite accurately. The AUPP can be easily derived from the area ratio parameter as shown by Equation 8

$$AUPP = 900 * D_0 * (1 - A_r) \quad \text{Equation 8}$$

AUPP = the area under the pavement profile in mm²

D₀ = Maximum central deflection under the FWD load in mm

A_r = Area ratio as defined by Equation 1

The Circly simulated data was used to correlate the AUPP computed based on the FWD simulations and the tensile strain at the bottom of the asphalt concrete layer based on the standard axle load. Figure 5b and Equation 9 show an excellent correlation between AUPP parameter and the tensile strain at the bottom of the asphalt concrete layer with a coefficient of determination, R² of 0.98.

Figure 5 b

$$\begin{aligned} \varepsilon_t &= 2 * 10^{-6} * AUPP^{0.912} \\ R^2 &= 0.98 \end{aligned} \quad \text{Equation 9}$$

The normalized area ratio was also found to be reasonably correlated with the maximum tensile strain at the bottom of the asphalt concrete layer with a coefficient of determination, R²=0.87 as shown in Figure 5c and Equation 10.

$$\begin{aligned} \varepsilon_t &= 2. * 10^{-4} * Ar^{1-0.914} \\ R^2 &= 0.867 \end{aligned} \quad \text{Equation 10}$$

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Therefore, the normalized area ratio as a single parameter is reasonably well correlated with both compressive strain at the top of the subgrade and the maximum tensile strain at the bottom of asphalt. Thus, the normalized area ratio can be correlated with both the rutting and asphalt fatigue performance when ranking pavement sections at the network level. For the sake of more accuracy, when calculating the remaining service life, the normalised area ratio can be used to calculate the remaining life in rutting while the AUPP can be used to predict the remaining service life in fatigue.

Figure 5c

Prediction of the Remaining Service Life

With the strong correlation between the pavement critical responses namely, the maximum compressive strain at the top of the subgrade and the maximum tensile strain at the bottom of the asphalt concrete layer and the normalized area ratio, curvature function and AUPP, the remaining service life of pavement sections can be predicted.

Prediction of fatigue life

Most of the fatigue models utilized in the mechanistic empirical pavement design can be expressed in the form given by Equation 11.

$$N_f = \alpha \left(\frac{1}{\varepsilon_t} \right)^\beta \quad \text{Equation 11}$$

N_f = Number of axle repetitions for fatigue failure

ε_t = Maximum tensile strain at the bottom of the asphalt layer.

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α and β are material constants

By the substituting the tensile strain given by Equation 7 and 9 the fatigue life can be calculated in terms of pavement curvature or Area Under Pavement Profile (AUPP) parameters as shown by Equations 12 and 13.

$$N_f = \alpha \left(\frac{1}{2.3 * 10^{-3} * \delta + 2 * 10^{-5}} \right)^\beta \quad \text{Equation 12}$$

$$N_f = \alpha \left(\frac{1}{2 * 10^{-6} * AUPP^{0.912}} \right)^\beta \quad \text{Equation 13}$$

Where

N_f = number of axle load repetitions to fatigue failure

δ = Pavement surface curvature= $(D_0 - D_{200})$

AUPP= Area under pavement profile

α and β are material constants

Predictions of permanent deformation

Several pavement mechanistic empirical design methods use the subgrade compressive strain criterion model similar to Equation 14 to prediction rutting failure.

$$N_f = \kappa \left(\frac{1}{\varepsilon_{zz}} \right)^\lambda \quad \text{Equation 14}$$

N_f = number of axle repetition to reach rutting failure

ε_{zz} = Compressive strain on the top of the subgrade

κ and λ = material regression constants

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By utilizing the compressive strain given by Equation 5, the rutting remaining service life can be predicted at the network level by Equation 15.

$$N_f = \kappa \left(\frac{1}{4 * 10^{-4} * A_r^{1.111}} \right)^\lambda \quad \text{Equation 15}$$

For the traffic data of the traffic growth and the average annual daily traffic (AADT), the number of years for fatigue and permanent deformation failure can be determined. The smaller number will be used as the remaining service life. The normalized area ratio, curvature function and the AUPP can be calibrated against Long Term Pavement Performance data (LTPP) to provide ranking of the pavement structural condition and remaining service life.

CONCLUSIONS

Computer simulations for 2880 flexible pavement sections were used to generate deflection bowl data under FWD loading and standard axle load. The pavement critical responses such as maximum tensile strain at the bottom of the asphalt concrete layer and the compressive strain at the top of the subgrade under the effect of the standard axle load were determined. The area ratio, normalized area ratio, pavement surface curvature and area under pavement profile parameters were used as simple deflection bowl parameters that can be calculated at the network level. The normalized area ratio was found to be well correlated with the normalized deflection ratio. Both area ratio and deflection ratios were found to be insensitive to subgrade condition, however, the normalized values of these two parameters: normalized area ratio and normalized

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deflection ratio are well correlated to subgrade condition. The normalized area ratio is also sensitive to the applied load and pavement response. The normalized area ratio was found to be well correlated with the compressive strain at the top of the subgrade and it is also reasonably correlated to the tensile strain at the bottom of the asphalt concrete layer. The pavement surface curvature and the area under pavement profile parameters are highly correlated to the tensile strain at the bottom of the asphalt concrete layer. The normalized area ratio parameter provides an excellent tool for road asset manager to rank and classify the structural condition of the pavement network and can be used with other parameters such as curvature function and area under pavement profile to predict the remaining service life.

REFERENCES

Austrroads, 2012. Guide to Pavement Technology Part 2: Pavement Structural Design, ISBN 978-1-921991-11-0, Sydney, Australia.

Coetzee, N F, Van Wijk, AJ and Maree, J.H. 1989. Impact deflection measurements Proceedings of the 5th Conference on Asphalt Pavements in Southern Africa, Swaziland.

Department of Transport and Main Roads (DTMR), 2012. Pavement Rehabilitation Manual.

Ferne, B.W., Langdale, P., Round, N., & Fairclough, R. 2009. Development of a calibration procedure for the U.K. highways agency traffic-speed deflectometer (pp. 111–117)

(Transportation Research Record: Journal of the Transportation Research Board, No. 2093).

Washington, DC: Transportation Research Board of the National Academies. doi:10.3141/2093-13.

Ferne, B.W., Langdale, P., Round, N., & Fairclough, R. 2009. Development of a calibration procedure for the U.K. highways agency traffic-speed deflectometer (pp. 111–117)

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(Transportation Research Record: Journal of the Transportation Research Board, No. 2093).

Washington, DC: Transportation Research Board of the National Academies. doi:10.3141/2093-13.

Garg, N., and Thomson, M. R. 1998. Mechanistic-Empirical Evaluation of the Mn/Road Low Volume Road Test Sections. Final Report No. FHWA-IL-UI-262, the Illinois Department of Transportation, Springfield, IL.

Hoffman, M.S. & Thompson, M.R. 1981. Mechanistic Interpretation of Nondestructive Pavement Testing Deflections, Civil Engineering Studies, Transportation Engineering Series No.32, University of Illinois at Urbana-Champaign.

Horak, E and Emery, S. 2006. Falling weight deflectometer bowl parameters as analysis tool for pavement structural evaluations, Proceedings, 22nd Australian Road Research Board (ARRB) International conference, Brisbane, Australia.

Kim, R. Y. and Park, H. 2002. Use of Falling Weight Deflectometer Multi-Load Data for Pavement Strength Estimation, FHWA Final Report No. FHWA/NC/2002-006.

Lee, Y. C. 1997. Condition Assessment of Flexible Pavements using FWD Deflections. Ph. D. Dissertation, North Carolina State University, Raleigh, NC.

Murphy, M. R. 1998. A Mechanistic-Empirical Approach to Characterizing Subgrade Support and Pavement Structural Condition for Network-level Applications, PhD Dissertation, The University of Texas at Austin, Texas.

Rada, G.R. 2009. Moving pavement deflection testing: the future?, VI ALACPA Airport Pavements Seminar and IV FAA workshop, Sao Paulo, Brazil.

Rada, G.R., Daleiden, JF and Yu, H.T. 2010. Moving Pavement deflection testing measurements, 48th Transportation Infrastructure conference, Sao Paulo, Brazil.

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Romanoschi, S. and Metcalf, B. 1999 . Simple Approach to Estimation of Pavement Structural Condition,” Transportation Research Record 1652, Washington, D.C..

Saleh, M. 2014. Simplified approach for structural capacity evaluation of flexible pavements at the network level. International Journal of Pavement Engineering.

doi:10.1080/10298436.2014.993202.

Saleh, M. 2015. Multi-scale criteria for structural capacity evaluation of flexible pavements at network, level. The Transportation Research Board annual meeting, Washington, DC.

Saleh, M. 2015. Utilisation of the deflectograph data to evaluate pavement structural condition of the highway network, Journal of Road Materials and Pavement Design

DOI:10.1080/14680629.2015.1064823.

Scullion, T. 1988 .Incorporating a Structural Strength Index into the Texas Pavement Evaluation System, Research Report 409-3F, Texas Transportation Institute, Texas.

Thompson, M. R. 1989. Area Under the Pavement Profile to Predict Strain,” Informal Presentation at FWD Users Group Annual Meeting, Indianapolis, IN.

Thompson, M. R., and Elliot, R. P. 1985. ILLI-PAVE-Based Response Algorithms for Design of Conventional Flexible Pavements”, Transportation Research Record 1043, TRB, Washington, D. C., pp. 55-57.

Wardle, L., *CIRCLY Software: A multilayer linear analysis Computer Program*, Mincad Systems, Melbourne, Australia, 2012.

Zhang, Z., Manuel, L., Damnjanovic, I. and Li, Z. 2003. Development of a New Methodology for Characterizing Pavement Structural Condition for Network- Level Applications, Research Report 0-4322-1, Center for Transportation Research, Bureau of Engineering Research, The University of Texas at Austin.

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Figure 5c The relationship between maximum central deflection and the normalized area ratio for 1964 FWD tests carried out on flexible pavement consist of asphalt concrete over granular base in Queensland, Australia

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Figure 5d The relationship between maximum central deflection and the normalized area ratio for 1916 FWD tests carried out on flexible pavement with cement treated base, Queensland, Australia

Figure 6a Relationship between maximum tensile strain at the bottom of the asphalt concrete layer and the pavement surface curvature based on Circly simulations

Figure 6b Maximum tensile strain at the bottom of the asphalt concrete layer and area under the pavement profile (AUPP)

Figure 6c The relationship between the maximum tensile strain at the bottom of asphalt concrete layer and the normalized area ratio

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Table 1 Circly Computed Deflections under FWD Loadings for Pavement Sections 1a and

1b

		Pavement Section 3a	Pavement Section 3b
	Column1	Strong Pavement/Weak Subgrade	Strong Pavement /StrongSubgrade
Deflections in mm at different offests from load	D ₀	0.5196	0.2438
	D ₅₀	0.5178	0.2422
	D ₁₀₀	0.5122	0.2371
	D ₁₅₀	0.5004	0.2262
	D ₂₀₀	0.4876	0.2147
	D ₂₅₀	0.4781	0.2066
	D ₃₀₀	0.4688	0.1992
	D ₃₅₀	0.4596	0.1921
	D ₄₀₀	0.4502	0.1852
	D ₄₅₀	0.4409	0.1784
	D ₅₀₀	0.4314	0.1719
	D ₅₅₀	0.422	0.1655
	D ₆₀₀	0.4126	0.1593
	D ₆₅₀	0.4033	0.1534
	D ₇₀₀	0.394	0.1476
	D ₇₅₀	0.3849	0.1421
	D ₈₀₀	0.3759	0.1369
	D ₈₅₀	0.367	0.1318
	D ₉₀₀	0.3583	0.127
Layers Moduli (MPa)	E _{AC}	4500	4500
	E _{base}	350	350
	E _{subgrade}	30	100
layers Thicknesse s (mm)			
	h ₁	250	250
	h ₂	500	500
Parameters	D _r =D ₂₅₀ /D ₀	0.920	0.8474
	Area ratio (A _r)	0.850	0.7464
	Normalized area ratio (A _r ')	1.635	3.0616

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Figure 1a

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Figure 1b

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Figure 2a

Saleh, M.

Figure 2b

Saleh, M.

Figure 2c

Saleh, M.

Figure 2d

Saleh, M.

Figure 3a

Saleh, M.

Figure 3b

$$E_v=20\text{MPa}-120 \text{ MPa } \nu_h=\nu_v=0.45, \\ E_h=0.5 E_v$$

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Figure 3c

Saleh, M.

Figure 3d

Saleh, M.

Figure 4a

Saleh, M.

Figure 4b

Saleh, M.

Figure 5a

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Saleh, M.

Figure 5b

Figure 5c

Saleh, M.

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Saleh, M.

Figure 5d

Saleh, M.

Figure 6a

Saleh, M.

Figure 6b

Saleh, M.

Figure 6c