# Development of a Correction Method for the Current Pavement ME Methodology in Equivalent Loading Frequency Calculation

P. Chen
*School of Civil Engineering and Engineering Management, Guangzhou Maritime University, Guangzhou, Guangdong Province, 510725, China*

K. Chatti, B. Cetin
*Department of Civil and Environmental Engineering, Michigan State university, East Lansing, MI, USA*

ABSTRACT: The AASHTOWare Pavement ME Design uses linear-elastic analysis to simulate the strain responses under axle loadings, and it relies on equivalent loading frequencies to determine the representative elastic modulus of the asphalt concrete (AC) layer. The Pavement ME employs a highly simplified approach for calculating equivalent loading frequency, which often leads to an overestimation of these frequencies, particularly near the AC surface. This paper presents a simple correction method for the current Pavement ME method in loading frequency calculations based on two novel frequency calculation methods. The correction procedure is straightforward, computationally efficient, and readily implementable within the Pavement ME design software. The corrected loading frequencies are validated by calculating critical strains using these frequencies in three representative pavement structures under Michigan's climate conditions. The results indicate that the corrected loading frequency significantly enhanced the accuracy of vertical strain predictions, particularly at the shallow depth of the AC layer.

## 1 INTRODUCTION

The primary advantage of mechanistic-empirical design procedures over the 1993 AASHTO Guide is its ability to allow pavement engineers to fundamentally analyze a variety of materials, loading conditions, and corresponding responses, rather than solely relying on observed pavement performance and ride quality. However, the accuracy of the Pavement ME method in estimating loading frequencies has been scrutinized in several studies (Al-Qadi et al., 2008a, 2008b; Losa & Di Natale, 2012; Ulloa et al., 2013), largely due to its dependence on overly-simplified and inaccurate assumptions.

To examine the loading time calculated by the Pavement ME method, Al-Qadi et al. (2008a) simulated vertical stress pulses with a 3-D finite element model by the Abaqus software, incorporating the viscoelastic properties of the AC material measured from the laboratory. This method defines the boundary of the loading duration by locating the instances at which the slope of the vertical stress pulse shifts from negative to positive. Then the loading frequency is calculated as the reciprocal of the loading time (*f=1/t*). Their research concluded that, relative to the proposed method, the Pavement ME method overestimates loading frequency by up to 300% near the surface of the pavement layer, with both methods' frequency estimates gradually converging as depth increases. Hu et al. (2010) simulated the vertical stress pulse based on the layered elastic theory and found that the loading duration is not only a function of the vehicle speed and depth of interest, but also a function of the moduli ratio between the layer of interest and the directly underlying layer. Al-Qadi (2008b) performed FFT (Fast Fourier Transform) for vertical stress pulses measured from the field testing and took the frequency values that corresponded to the centroid of area formed by the FFT amplitude curve as the dominant frequency of the pulses. These frequencies were then compared with those calculated by the Pavement ME method (*f=1/t*) and the angular frequency "*f=1/(2πt)*". Results showed that the Pavement ME method exhibits errors from 40% to 140% depending on vehicle speed and pavement depth. Losa & Di Natale (2012) developed a method to calculate equivalent loading frequencies for three directions (longitudinal, transverse, and vertical) using an iteration procedure without determining the loading time. The equivalent frequency is iteratively adjusted and employed to back-calculate the elastic modulus until the critical strains determined by this back-calculated elastic modulus converge with those obtained from dynamic viscoelastic analysis. The study by Losa & Di Natale (2012) suggests that the Pavement ME method generally overestimates loading frequencies, whereas Al-Qadi's approach tends to underestimate them. Chen et al. (2024)

comprehensively evaluated the accuracy of the Pavement ME method by comparing the Pavement ME method with two novel methods in terms of frequency and critical strains predicted by loading frequencies. The findings suggest that the Pavement ME significantly overestimates loading frequencies, consequently leading to an underestimation of vertical strain near the AC surface. However, it provides a reasonably accurate prediction of horizontal tensile strain at the bottom of the AC layer.

This paper presents a correction method that addresses limitations in the Pavement ME approach for calculating equivalent loading frequencies. The proposed method is straightforward in its application and can be readily integrated into the Pavement ME design software.

## 2 LIMITATIONS OF THE ORIGINAL PAVEMENT ME METHOD

The original Pavement ME method transfers the AC layer into an equivalent layer with a different thickness (effective thickness) as a function of the ratio between the AC and subgrade moduli based on the revised Odemark's method. Then it assumes the vertical stress pulse propagates linearly at 45 degrees within the transformed AC layer. Finally, the frequency is calculated as the reciprocal of the loading time, which is equal to the pulse width divided by the vehicle speed (ARA 2001).

Three main flaws have been identified in the Pavement ME method (Hu et al., 2010; Chen et al. 2024). Firstly, the frequency-time relationship of "$f=1/(2t)$" should be used, instead of "$f=1/t$". Secondly, the vertical stress distribution slope is influenced by the ratio between the moduli of the AC layer and the layer immediately beneath it, typically the base layer, instead of the subgrade layer. In addition, the actual layer moduli should be used instead of generic values. Thirdly, the Pavement ME method always underestimates the pulse width near the surface of the AC layer.

## 3 CORRECTION PROCEDURE

The correction procedure addresses the three limitations of the original Pavement ME method through a two-stage approach, incorporating two novel methodologies proposed by Chen et al. (2024): the centroid of PSD (Power Spectral Density) and the Equivalent Frequency, respectively. The centroid of PSD method takes the weighted center under the PSD (equals the square of the Fourier amplitude) curve as the dominant frequency of the loading pulse. The Equivalent Frequency is determined by iteratively adjusting the frequency value until the responses obtained from linear-elastic analysis using these loading frequencies align with those produced by viscoelastic analysis.

Twelve hypothetical cases with a combination of different vehicle speeds, AC thickness, stiffness, and temperature (Al-Qadi et al. 2008a, Chen et al. 2024) are utilized to calculate the pulse width by the centroid of PSD method and the Equivalent Frequency method. Examples of vertical stress pulse widths obtained by different methods at mid-temperature (25°C) for both thin and thick pavement are shown in Figure 1.

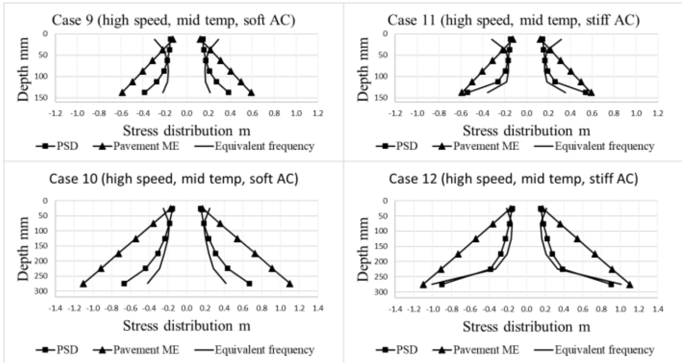


Figure 1. Pulse width by Pavement ME, PSD method, and Equivalent Frequency for vehicle speed of 80 km/h, soft and stiff AC layer at 25°C, and base layer with 207 MPa.

### 3.1 *Stage I: Correction for Vertical Stress Distribution Slope*

The centroid of PSD method generally agrees well with the Equivalent Frequency except for near the AC surface. In stage one, the centroid of PSD method is used to derive the vertical stress pulse distribution slope along the depth as a function of the ratio between the moduli of the AC layer and the base layer. The centroid of PSD method does not calculate the pulse duration explicitly. Therefore, its pulse duration must be indirectly estimated using the time-frequency relation of "$f=1/(2t)$" (Chen et al. 2024). As can be seen in Figure 1, the vertical stress distribution slope obtained by the centroid of the PSD method does not follow a linear trend. Instead, the profile exhibits a concave shape that can be characterized by two distinct slopes for the upper 75% and the lower 25% of the AC layer thickness, as illustrated in Figure 2 (Chen 2024).

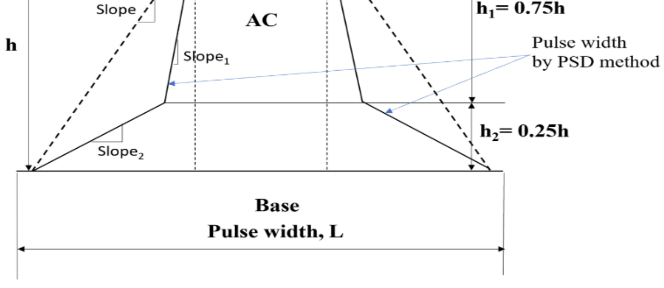

Figure 2. Simplified vertical stress distribution slope by the centroid of PSD method.

The average modulus of the AC layer, as calculated by Equation 1, ensures that when the modulus of each AC sub-layer is substituted with a uniform average value, the overall vertical strain remains unchanged.

$$E_{AC} = \left(\frac{1}{h_{AC}}\sum_{1}^{n} h_i \times \frac{1}{E_i}\right)^{-1} \quad (1)$$

where: $E_{AC}$ is the average elastic modulus of the AC layer; $h_{AC}$ is the thickness of the AC layer; $h_i$ is the thickness of each sublayer; $n$ is the number of sublayers; $E_i$ is the modulus of each sublayer, which is a function of temperature and loading frequency calculated by the Pavement ME method.

According to Odemark's method, the gradient of the vertical stress distribution within the AC layer is linearly dependent on $(E_{AC}/E_{Base})^{1/3}$, where $E_{Base}$ is the modulus of the base layer. The slope derived from the centroid of PSD method (dashed lines in Fig. 2) is calculated and plotted against $(E_{AC}/E_{Base})^{1/3}$ for the twelve cases as shown in Figure 3. The trend line in Figure 3 demonstrates the linear relationship between the slope and $(E_{AC}/E_{Base})^{1/3}$.

The base modulus across the twelve cases remains consistent at 207 MPa. To extend the relationship depicted in Figure 3 to other base moduli, twenty-four additional hypothetical cases, designated as cases 13 through 36, were developed. These cases feature AC moduli ranging from 345 MPa to 6,895 MPa and base moduli ranging from 69 MPa to 689 MPa. The analysis results for cases 13 through 36 are presented in Figure 4, with the linear trend line coefficient closely aligning with that observed in Figure 3, suggesting that the modulus of the base layer exerts minimal influence on the slope of the vertical stress distribution. Consequently, the slope can be determined using Equation 2.

$$Slope = \left(\sqrt[3]{\frac{E_{AC}}{E_{base}}}\right)^{-1} \quad (2)$$

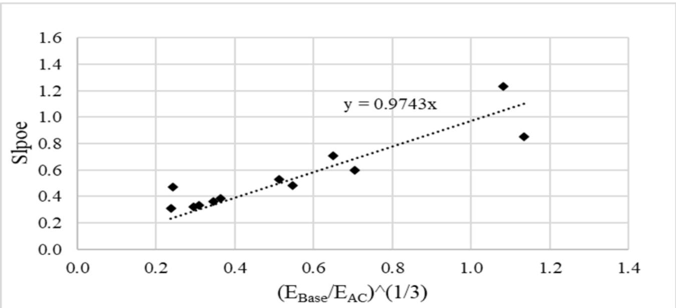


Figure 3. Vertical stress pulse distribution slope versus the ratio between AC and base moduli (Cases 1 to 12).

As previously noted, the stress pulse distribution slope by the centroid of PSD method comprises two distinct segments for the upper 75% and the lower 25% of the layer thickness. An analysis similar to that illustrated in Figures 3 and 4 is conducted to determine the ratio (denoted as $R_{75}$) between the actual pulse width at a depth corresponding to 75% of the AC thickness and the pulse width defined by the slope calculated by Equation 2 for cases 1 to 36. The results indicate that $R_{75}$ roughly equals 1.35 times the quantity of $(E_{Base}/E_{AC})^{1/3}$.

Once $R_{75}$ is obtained, the stress pulse distribution slopes and the corresponding pulse widths can be easily calculated by Equations 3 to 6:

$$Slope_1 = \frac{Slope}{R_{75}} = 0.741 \quad (3)$$

$$Slope_2 = \frac{0.25}{1/Slope - 0.75/Slope_1} \quad (4)$$

$$L_1 = 2 \times \left(\frac{h}{Slope_1} + a_c\right) \quad (5)$$

$$L_2 = 2 \times \left(\frac{h - 0.75h_{AC}}{Slope_2} + \frac{0.75h_{AC}}{Slope_1} + a_c\right) \quad (6)$$

where $Slope$ is the uniform stress pulse distribution slope obtained from Equation 2; $Slope_1$, $L_1$ and $Slope_2$, $L_2$ are stress pulse distribution slopes and the corresponding pulse widths within the upper 75% and lower 25% of the AC layer thickness, respectively; $h$ is the depth of interest; $h_{ac}$ is the thickness of the AC layer; $a_c$ is the radius of the tire footprint.

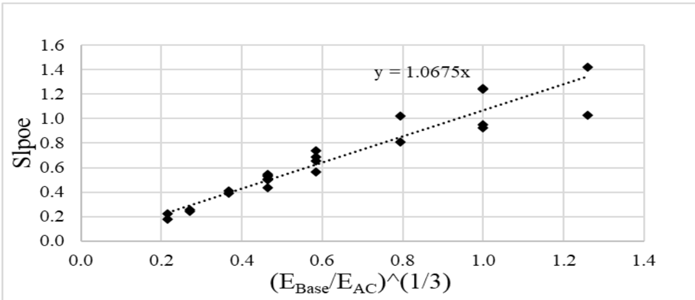


Figure 4. Vertical stress pulse distribution slope versus the ratio between AC and base moduli (Cases 13 to 36).

## 3.2 *Stage II: Correction for the stress pulse near the surface of the AC layer*

As can be seen from Figure 1, the pulse width determined using the centroid of the PSD method is considerably shorter than that obtained through the Equivalent Frequency method at the AC surface. However, this discrepancy diminishes progressively with increasing depth, and the pulse widths determined by these two methods tend to converge at a depth of approximately 65 mm regardless of pavement structures (Chen 2024). The pulse widths derived from Stage I must be refined by applying correction factors specifically for the upper 65 mm of the AC layer as defined in Equation 7.

$$CF = (L_e - L_1)/(2 \times a_c) \quad (7)$$

where $CF$ is the correction factor; $a_c$ is the radius of the tire-pavement contact footprint; $L_e$ is the pulse width determined by the Equivalent Frequency. The correction factor reaches its maximum value at the AC surface and decreases linearly until it reaches zero at a depth of 65 mm. The correction factor is also affected by the modulus of the AC layer, though it exhibits significantly less sensitivity compared to the pulse distribution slope. A similar analysis to that depicted in Figure 2, as conducted by Chen (2024), indicates that the correction factor at the surface is proportional to the logarithm of the AC modulus. The correction factor, within the top 65 mm of the AC layer can be calculated by Equations 8 and 9:

$$CF_{max} = 0.62 \times \log(145 \times E_{AC}) \quad (8)$$

$$CF = \frac{-CF_{max}}{2.5} h + CF_{max} \quad (9)$$

where $CF_{max}$ is the correction factor at the surface of the AC layer; $E_{AC}$ is the average AC modulus in MPa.

By applying the correction factor, the pulse width and loading frequency for the corrected Pavement ME method can be determined using Equations 10 and 11, respectively:

$$L_{corrected} = L_i + CF \times 2a_c \quad (10)$$

$$f_{corrected} = \frac{1}{2 \times L_{correct}/V} \quad (11)$$

where $L_{corrected}$ is the pulse width of the corrected Pavement ME frequency method; $L_i$ (i = 1, 2) is the pulse width calculated by Equations 5 or 6; and $V$ is the vehicle speed.

## 4 VERIFICATION OF THE CORRECTED PAVEMENT ME LOADING FREQUENCY

The corrected Pavement ME loading frequency calculated by Equation 11 is verified by comparing critical strains predicted by linear elastic analysis using these frequencies with those obtained from dynamic viscoelastic analysis. The simulation scenarios involve three hypothetical pavement structures located in the climatic conditions of East Lansing, Traverse City, and Detroit, Michigan, subjected to a 16-ton tandem-axle load traversing at a velocity of 96 km/h. Two temperature quintiles from July were selected for analysis, as July represents the hottest month of the year, thereby reflecting the most critical conditions for pavement responses.

As shown in Figure 5, the corrected loading frequency substantially improved the prediction of vertical strain at the shallow depth of the AC layer, closely aligning with viscoelastic analysis results within Quintile 5 (highest temperature) across all three pavement structures. The effect of the corrected loading frequency on improving vertical strain prediction is less evident in Quintile 1, which is of lower criticality for pavement responses, as it represents the lowest temperature in July. In summary, the correction procedure markedly enhances the accuracy of the Pavement ME method in predicting vertical strains near the AC surface.

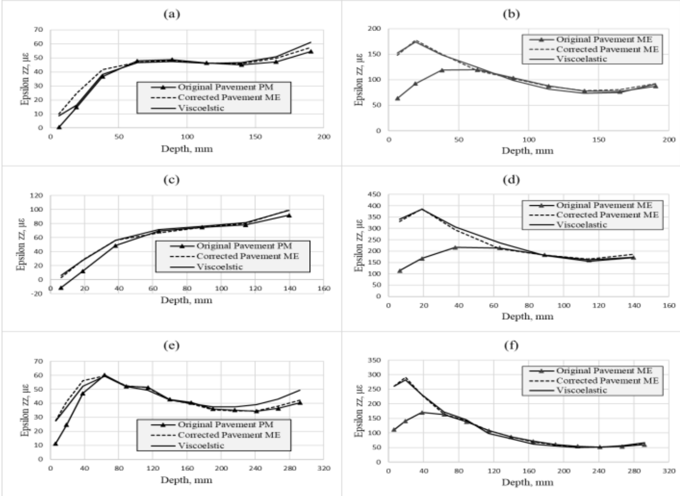


Figure 5. Vertical strains predicted by different methods (a) Quintile 1 of July for East Lansing climate; (b) Qquintile 5 of July for East Lansing climate; (c) Quintile 1 of July for Traverse City climate; (d) Quintile 5 of July for Traverse City climate; (e) Quintile 1 of July for Detroit climate; (f) Quintile 5 of July for Detroit climate.

## 5 REFERENCES


Al-Qadi, I. L., Elseifi, M. A., Yoo, P. J., Dessouky, S. H., Gibson, N., Harman, T., D'Angelo, J., & Petros, K. (2008b). Accuracy of current complex modulus selection procedure from vehicular load pulse: NCHRP Project 1-37A mechanistic-empirical pavement design guide. Transportation research record, 2087(1), 81-90.

Al-Qadi, I. L., Xie, W., & Elseifi, M. A. (2008a). Frequency determination from vehicular loading time pulse to predict appropriate complex modulus in MEPDG. Asphalt Paving Technology-Proceedings, 77, 739.

ARA, Inc., ERES Division. (2001). Appendix CC-3 of the Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. NCHRP 1-37A. https://onlinepubs.trb.org/onlinepubs/archive/mepdg/2appendices_CC.pdf

Chen, P. (2024). Impact of Equivalent Axle Loading Frequencies on Critical Strains and Distress Predictions in Asphalt Concrete Pavements (Doctoral dissertation, Michigan State University).

Chen, P., Chatti, K., & Cetin, B. (2024). Evaluation of the Accuracy of Pavement ME Methodology in Calculating Equivalent Loading Frequency and Its Effect on Strain Response Predictions in Flexible Pavements. Journal of Transportation Engineering, Part B: Pavements, 150(1), 04023042.

Hu, X., Zhou, F., Hu, S., & Walubita, L. F. (2010). Proposed loading waveforms and loading time equations for mechanistic-empirical pavement design and analysis. Journal of Transportation Engineering, 136(6), 518-527.

Losa, M. & Di Natale, A. (2012). Evaluation of representative loading frequency for linear elastic analysis of asphalt pavements. Transportation research record, 2305(1), 150-161.

Ulloa, A., Hajj, E. Y., Siddharthan, R. V., & Sebaaly, P. E. (2013). Equivalent loading frequencies for dynamic analysis of asphalt pavements. Journal of Materials in Civil Engineering, 25(9), 1162-1170.