Quantitative Assessment of the Effect of Wide-Base Tires on Pavement Response by Finite Element Analysis

Osman Erman Gungor, Jaime A. Hernandez, Angeli Gamez, and Imad L. Al-Qadi

Various studies have shown that the new-generation wide-base tire (WBT) for trucks causes more damage to pavement than does the dual-tire assembly (DTA). However, there is no substantive approach that quantifies the difference in pavement responses produced by WBTs and the DTA. This study fills this gap by developing linear equations that connect pavement responses produced by these two tire types. Equations were developed for 10 different pavement responses through 480 finite element method simulations (240 for the DTA and 240 for WBTs) that were run in ABAQUS with the same material properties and pavement structures. The only difference was the contact stresses and contact areas that were measured under the same axle load for WBTs and the DTA. The cases modeled in simulations were selected to capture extreme conditions, that is, thick and thin pavement structures with strong and weak material properties. The equations will help pavement researchers to understand quantitatively the effect of WBTs on pavement responses as compared with the DTA. The low resultant prediction error, 10%, allows linear equations to be implemented through the application of adjustment factors on mechanistic pavement design guides such as the Mechanistic–Empirical Pavement Design Guide, which are unable to simulate WBT loading realistically. To predict pavement damage accurately, the pavement analysis should consider the WBT market penetration in the United States (approximately 10%) and the partial use of WBTs on truck axles. The impact of WBTs on pavement should be evaluated in the context of economic and environmental benefits.

According to a 2013 U.S. Environmental Protection Agency report, 27% of greenhouse gas emissions was produced by the transportation sector (1). These emissions make transportation the second-highest source of greenhouse gas after electricity production (31%). Many attempts have been made in the past decade to reduce the environmental impact of the transportation sector. Replacing conventional dual tires with wide-base tires (WBTs) is one such development related to pavement engineering in the transportation sector.

WBTs were introduced to the market in the early 1980s and have been extensively used, especially in Europe and Canada. Improved fuel efficiency, better handling and braking, and reduced gross weight, emissions, tire replacement, and maintenance cost are some reported benefits of using WBTs (2–4). On the other hand, even though trucks equipped with WBTs can be safely brought to the side of the road when a tire blows out, a safety issue associated with the failure of a WBT has also been reported. In the event of a blown-out WBT, there is no other tire to help the driver reach the next service station, as there is with a dual-tire assembly (DTA).

The main concern about the WBT that has been raised by state and federal transportation agencies concerns the pavement damage caused by WBTs compared with the DTA. Several studies have investigated the effect of WBTs on pavement performance. Most of these studies have agreed that WBTs generally cause more damage to the pavement than does the DTA. However, none of these studies quantified the difference in pavement responses generated by WBTs as compared with the DTA.

This study fills this gap by presenting linear equations that connect pavement responses produced by these two different tire types. The equations were developed for 10 different pavement responses by using a total of 480 finite element (FE) method simulations that were run in ABAQUS with the same material properties and pavement structures. The cases simulated in ABAQUS were selected to capture extreme conditions, that is, thick and thin pavement structures with strong and weak material properties. The tire types considered in the simulations were WBT 445/50 R22.5 and DTA 275/80 R22.5, which are the most commonly used in the market. The equations developed provide pavement researchers with a more comprehensive insight into the effect of WBTs on pavement behavior. Additionally, this study provides pavement design guides, such as the Mechanistic–Empirical Pavement Design Guide (MEPDG) (5), with the opportunity to consider WBT loading without having to implement advanced structural analysis methods such as the FE method.

LITERATURE REVIEW

Among the major efforts made in the transportation sector to reduce the sector’s environmental impact was the replacement of the DTA with WBTs. WBTs introduced several advantages, such as reduced fuel costs and improved braking and handling. However, pavement researchers and engineers raised a concern that WBTs might cause more damage to pavement than did the DTA because WBTs have a smaller contact area. Many studies have been conducted to investigate the effect of WBTs on pavement structure. These studies can be classified into two groups:

- Studies conducted between the 1980s and 2000 that suggested WBTs caused more damage to pavement than did the DTA and
that led the tire industry to produce the so-called new-generation WBT with a wider tread than its predecessors and

- Studies that investigated WBTs.

Following is a summary of the studies conducted to estimate the damage effects of first-generation and later WBTs.

In 1986 and 1989, Huhtala and colleagues presented two studies using accelerated pavement testing on three different pavement sections with various loading conditions (6, 7). Comparison of these two tire types was made on the basis of the pavement response of tensile strain at the bottom of asphalt concrete (AC) and vertical pressure at the top of the subgrade. They concluded that WBTs caused approximately four times more damage to pavement than did the DTA. Similar conclusions were reported by Sebaaly and Tabatabaee in 1989, who found that WBTs resulted in 50% greater tensile strain at the bottom of AC and 25% greater compressive stress with hot-mix asphalt compared with dual tires (8). Akrain et al. used multidepth deflectometers to quantify the damage effects of the DTA as compared with WBTs (9). Two different pavement structure types were considered in the experiments: thin and thick pavements. It was reported that WBTs produced 2.5 times and 2.8 times more rutting damage than the DTA on thin and thick pavements, respectively. Similarly, Bonaquist stated that WBTs produced two times more permanent deformation and caused 25% lower fatigue life than the DTA (10).

The WBT with wider tread was introduced to the market at the beginning of the 2000s. In 2001, experimental studies were conducted in Europe to investigate the effect of WBTs on pavement responses (11). Two different pavement sections were built in the United Kingdom to compare the so-called new-generation WBT (495/45R22.5) with the traditional WBT (385/65R22.5). This study found that the traditional WBT-385 caused 50% and 70% more rutting damage to medium-thick and thin flexible pavement, respectively. The effect of WBTs on thick pavement was evaluated in Germany, where WBTs were compared with the DTA; it was reported that WBTs caused 30% more rutting damage than did the DTA. Another comparison between the DTA and WBTs was conducted in France on very thick and stiff pavement. This study showed that there was no significant difference between these two types of tires for this type of pavement. An extensive test matrix was performed in Virginia that included 12 different pavement sections, two different axle loads, and four different tire pressures (12, 13). Comparison of WBTs with the DTA found that the former type of tire was, in general, less damaging. Two WBT tires, WBT-425 and WBT-455, and the DTA were compared to assess their effects on full-depth pavement at the University of Illinois at Urbana–Champaign (14, 15). WBT-425 was found to be more damaging than WBT-455.

Most studies have come to the conclusion that both first-generation WBTs and new-generation WBTs cause more pavement damage than the DTA. However, most of these conclusions have been reached on the basis of a limited number of pavement structures, loading cases, and material characterizations. Experimental evaluation of pavement performance is not only time-consuming but also expensive and cumbersome. None of the past studies has proposed a general mathematical relationship connecting these two tire types in terms of pavement behavior. This study fills this gap in the literature by proposing linear equations that convert the pavement responses obtained from the DTA to those for WBTs. FE analysis was used to develop the equations. The use of FE analysis in this study gave the advantage of considering a wide variety of cases for pavement structure, material properties, and loading conditions that would not be feasible in any experimental study.

### THREE-DIMENSIONAL FE MODEL

Simulating flexible pavement is a challenging task. Other than its geometry, every component of the simulation, such as the loading conditions and material characterization, is complicated. The tire applies nonuniform and three-dimensional contact stresses on the pavement. Asphalt material exhibits viscoelastic behavior, meaning that its behavior depends on time (aging), temperature, and frequency of loading. The stiffness of the granular material depends on the stress level to which it is exposed. Granular material shows stiffer behavior under a high stress level and becomes softer when the stress is low. Moreover, the material behaves differently in each principal direction, that is, it is considered an anisotropic material. The literature clarifies the significant effect of these conditions on pavement responses (16–19). Therefore, it is important to capture the effects while simulating pavement behavior under the tire load to compute the pavement responses accurately.

Linear elastic theory (LET) is the current analysis approach used in mechanistic empirical design guides. However, the theory fails to simulate pavement–tire interaction realistically because of its inability to adopt some of the above-mentioned conditions. Linear elastic characterization of asphalt concrete and base materials, a spring model assumption for layer interface, vertical uniform tire pressure, and a circular contact area are only some examples of the unrealistic simplifications and assumptions of LET. Besides the fact that these assumptions may lead to inaccurate pavement response calculation for DTA loading, dividing axle load by tire pressure is not a realistic representation of the WBT contact area.

The FE method, on the other hand, has proved to be a promising numerical method that could successfully simulate loading conditions and account for nonlinearity in material characterization. Therefore, the FE method has gained popularity over the past decade. The pavement FE model presented in this paper is the ultimate version of more than 10 years of ongoing research (2, 16, 20–22). The model is capable of considering the conditions omitted by LET. Moreover, the developed model has been successfully validated by using experimental field data from various pavement sections (23).

The key features of the developed FE model can be categorized into five different groups: model geometry and boundary conditions, loading conditions, material characterization, analysis method, and interface interaction model. A brief explanation for each key feature is given in the following sections. Details can be found in Al-Qadi et al. (23).

### Model Geometry and Boundary Conditions

The FE method of flexible pavement structure that was developed in commercial FE software, ABAQUS v 6.13, is given in Figure 1. It is known that the FE method generates more accurate results as the size of the element gets smaller, but that approach is computationally expensive. Therefore, mesh sensitivity analysis was performed to optimize accuracy and computation time. To perform mesh sensitivity analysis, an elastic FE model was compared with the LET software BISAR for six different critical pavement responses: maximum transverse and longitudinal tensile strain at the bottom of AC; maximum compressive strain within subgrade; and maximum vertical shear strain within AC, base, and subgrade. The model was refined until the difference in the results between the FE model and BISAR was approximately 5%.
Loading Conditions

LET assumes uniform static vertical pressures within a circular contact area. On the other hand, a tire applies three-dimensional and non-uniform contact stresses that were experimentally measured along with the realistic contact area. The FE method considers this true tire–pavement contact loading. Details about tire contact measurements can be found elsewhere (24). Figures 2 and 3 are representative sketches for the measured contact areas of a WBT and a DTA, respectively. These figures show clearly that tire footprint may not be simulated as a circular area, although the error may be less in the case of DTA. In addition to nonuniform contact stress, simulating the tire as a continuous moving load rather than a static steady load is another important realistic consideration in the developed model.

Material Characterization

Asphalt concrete was modeled as a linear viscoelastic material in the developed FE model. ABAQUS characterizes linear viscoelastic material by Prony coefficients obtained from the asphalt concrete master curve. Shear and relaxation moduli are then computed by assuming a constant Poisson’s ratio and Prony coefficients. The bulk and shear moduli equations used in ABAQUS are given in Equations 1 and 2. The Williams-Landell-Ferry function is also used to model time–temperature superposition of AC (Equation 3).

\[ G(t) = G_0 \left[ 1 - \sum_{i=1}^{n} G_i \left( 1 - e^{-\eta_i t} \right) \right] \]  
\[ K(t) = K_0 \left[ 1 - \sum_{i=1}^{n} K_i \left( 1 - e^{-\eta_i t} \right) \right] \]

where

- \( G \) = shear modulus;
- \( K \) = bulk modulus;
- \( t \) = reduced relaxation time;
- \( G_0 \) and \( K_0 \) = instantaneous shear and volumetric modulus, respectively; and
- \( G_i \), \( K_i \), and \( \eta_i \) = Prony series parameters.

In addition

\[ \log(\alpha_t) = \frac{-C_1(T - T_r)}{C_2 + (T - T_r)} \]

where

- \( \alpha_t \) = shift factor,
- \( C_1 \) and \( C_2 \) = regression coefficients,
- \( T \) = analysis temperature, and
- \( T_r \) = reference temperature.

In conventional pavement analysis approaches, both base and subgrade materials are characterized as linear elastic material. However, it has been clearly shown in the literature that the base material exhibits nonlinear stress-dependent anisotropic behavior. Although nonlinearity significantly affects the pavement responses for thin pavement, its effect is negligible for thick pavements where stress levels in base materials are low, as tire load is mostly distributed by the relatively thick AC layer. Therefore, to reduce computation cost, the base material was modeled as nonlinear stress-dependent cross-anisotropic material only for thin pavements. The MEPDG model (5) was used to characterize nonlinear material by Prony coefficients obtained from the asphalt concrete master curve. Shear and relaxation moduli are then computed by assuming a constant Poisson’s ratio and Prony coefficients. The bulk and shear moduli equations used in ABAQUS are given in Equations 1 and 2. The Williams-Landell-Ferry function is also used to model time–temperature superposition of AC (Equation 3).
stress-dependent cross-anisotropic behavior of the base materials (Equations 4–6).

\[ M_{v} = k_{v} \left( \frac{\sigma_{v}}{P_{r}} \right)^{n_{v}} \]  \hspace{1cm} (4)

\[ M_{h} = k_{h} \left( \frac{\sigma_{h}}{P_{r}} \right)^{n_{h}} \]  \hspace{1cm} (5)

\[ M_{s} = k_{s} \left( \frac{\sigma_{s}}{P_{r}} \right)^{n_{s}} \]  \hspace{1cm} (6)

where

- \( M_{v}, M_{h}, M_{s} \) = vertical, horizontal, and shear resilient modulus, respectively;
- \( \theta = \sigma_{1} + \sigma_{2} + \sigma_{3} \) = bulk stresses;
- \( \sigma_{d} = \) deviatoric stress;
- \( P_{r} = \) unit reference pressure; and
- \( k_{1}, k_{2}, k_{3}, k_{4}, k_{5}, k_{6}, k_{7}, k_{8}, k_{9} = \) regression coefficients.

Analysis Method

There are three commonly used methods for pavement analysis: static, quasi-static, and dynamic analysis. Static analysis assumes that the tire is not moving, although it can consider viscoelasticity in the analysis. Quasi-static analysis can model the tire as a moving load; however, it does not capture the inertial and damping effects. Therefore, dynamic analysis was used in this study to properly simulate moving tire loads with viscoelastic and nonlinear material characterization. The dynamic equation solved in ABAQUS is given in Equation 7. This equation can be solved with the implicit or explicit direct integration method. In this study, the implicit direct integration method was selected because it is more accurate for the level of frequencies observed in pavement simulations.

\[ [M][\ddot{U}] + [C][\dot{U}] + [K][U] = \{P\} \]  \hspace{1cm} (7)

where

- \([M] = \) mass matrix,
- \([C] = \) damping matrix,
- \([K] = \) stiffness matrix,
- \([P] = \) external force vector,
- \([\ddot{U}] = \) acceleration vector,
- \([\dot{U}] = \) velocity vector, and
- \([U] = \) displacement vector.

Interface Model

The model used for defining how two pavement layers interact with each other is another key parameter for pavement simulation. All AC layers were assumed to be fully bonded to each other in the developed model. On the other hand, AC–base and base–subgrade interaction were simulated with a Coulomb model. In this model, resistance of the movement was assumed to be proportional to the normal stress at the interface. In addition, a tolerance limit was set for shear strength above which two layers start sliding relative to each other in the case of AC–base interaction. If relative sliding occurred, the frictional stress was assumed to be constant.

SIMULATION MATRIX SELECTION

The inputs required for pavement simulations can be mainly divided into three groups: pavement structure (i.e., layer thicknesses and material properties), loading conditions, and material characterization parameters. The value for each of these input parameters can differ widely from one pavement section to another. It is an impossible task to simulate all possible pavement sections that combine all possible values for each inputs. The study of case selection (i.e., selection of layer thickness, axle loads, and tire pressures), therefore, was needed to determine parametric values required for the pavement simulation.

The linear equations were developed on the basis of regression analysis. As a rule of thumb, to increase reliability, it is important to stay in the range of inputs of regression-based functions. Therefore, it was decided to cover extreme values for each input to avoid extrapolation during the implementation of those equations.

The pavement sections were selected on the basis of two traffic volume conditions: low-volume and Interstate highways. The thicknesses were selected to vary between extreme conditions for these two road types (Table 1). A total of 10 different tire loadings were simulated. Axle loads and tire pressures were selected to cover extreme load conditions as well (Table 2).

The Long-Term Pavement Performance (LTTP) database was used to extract material properties for the AC. Approximately 1,000 complex modulus data were mined to obtain desired inputs for the pavement simulations. First, nominal maximum aggregate size (NMAS) was decided for each AC layer. A range of 9.5 mm to 12.5 mm was selected for NMAS for the wearing surface; ranges of 19.5 mm to 22.5 mm and 25 mm to 37.5 mm were considered to be typical NMAS

<table>
<thead>
<tr>
<th>TABLE 1 Pavement Structure Factorial</th>
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<tbody>
<tr>
<td>Pavement Layer</td>
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<tr>
<td>----------------</td>
</tr>
<tr>
<td>Wearing surface</td>
</tr>
<tr>
<td>Intermediate</td>
</tr>
<tr>
<td>Binder</td>
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<tr>
<td>Granular base</td>
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*Low-volume-road cases considered only one AC layer.

<table>
<thead>
<tr>
<th>TABLE 2 Selected Tire Loading Cases</th>
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<tbody>
<tr>
<td>Tire Type</td>
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<tr>
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</tr>
<tr>
<td>WBT</td>
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<tr>
<td>WBT</td>
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<td>WBT</td>
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<td>WBT</td>
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<td>DTA</td>
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for the intermediate and binder layer, respectively. Afterward, data were classified into groups on the basis of NMAS for each AC layer and filtered through statistical analysis. Finally, the remaining data were plotted and data representing one strong and one weak complex modulus were visually chosen for each AC layer.

To select appropriate material parameters for base and subgrade characterization, the database collected by Tutumluer et al. was used (25). This database has information to determine the \( k \)-values in Equations 4, 5, and 6 for 114 different granular materials. Stress levels observed in the field were estimated from Xiao et al. (26), and the resilient modulus of each granular material was calculated at those stress levels. The mean (\( \mu \)) and standard deviation (\( \sigma \)) of resilient modulus for all granular materials were computed. Then, weak and strong resilient test data were determined to capture extreme conditions on the basis of high and low stress levels. The lower and upper limits were set as \( \mu \pm 2\sigma \). The weak and strong base materials were selected as the ones that have a resilient modulus value closer to the lower and upper limits, respectively.

**RESULTS**

The objective was to find relationships for converting the pavement response resulting from the DTA into that for WBTs. A total of 240 cases were run in ABAQUS for these two different tire types and with the same material properties and pavement structures. The only difference was the tire–pavement contact, which was measured under the same axle load for WBTs and the DTA. After plotting the simulation results, a linear relation was observed between the pavement responses of the DTA and WBTs; therefore, this relationship is represented as linear functions of the DTA. Figures 4 and 5 show the linear equation developed for maximum tensile strain along the traffic and transverse directions at an AC surface and bottom of AC. The plots have two different lines: an equality line (\( y = x \)) and a line of fitted linear function. The equality line is solid and the fitted line is dashed. The purpose of the equality line is to demonstrate the significance of applying an adjustment factor to each particular response.

The linear equations developed a total of 10 different pavement responses. Because of the brevity of the paper, only four plots are presented here. The results for all pavement responses are given in Table 3 with the corresponding coefficients of determination (DTA and WBT refer to the pavement responses resulting from these two tire types).

**DISCUSSION OF RESULTS AND MAIN FINDINGS**

A total of 480 simulations (240 for the DTA, 240 for WBTs) were run in ABAQUS to develop a mathematical relationship for pavement responses resulting from these two different tire types. The resulting equation and the coefficient of determination can be found in the previous section. The following are significant observations regarding the effect of WBTs on pavement responses:

- The coefficients of the DTA variables (i.e., pavement response caused by DTA loading) in the equations are always greater than 1 for all responses. This indicates that WBTs caused higher responses than the DTA for the same axle load and tire inflation pressure, which might result in greater pavement damage.
The linear equations were developed for all cases without dividing the cases into subgroups. This means that these linear equations could be applied to DTA responses for predicting WBT response regardless of the material property (weak or strong AC or base characterization) and pavement structure (i.e., thick or thin pavement).

- That the coefficient of determination for all pavement responses is high—from 0.97 to 0.99—shows that these equations can be implemented to predict WBT loading for mechanistic pavement design guides, such as the MEPDG, where WBT loading cannot be simulated.
- The value of the coefficient of determination increases as depth of the pavement responses increases because the vertical contact stress becomes the governing factor on pavement responses as the effects of longitudinal and transverse contact stresses diminish.
- The aforementioned observation excludes the maximum tensile strain in traffic direction at an AC surface with the coefficient of the determination of 0.99. This exception is attributed to the location of the maximum tensile strain, which, although it occurs at an AC surface, is observed approximately 0.5 m away from the tire, where in-plane nonuniform contact stresses lose their effect on the pavement response.
- The most significant difference between WBT and DTA loading was observed on the maximum tensile strain in transverse direction at the bottom of AC. WBT loading produced approximately 60% higher response than DTA loading.
- The lowest coefficient of determination was observed for the maximum vertical shear strain within AC, because it is the pavement response most affected by three-dimensional nonuniform tire contact stress distribution as it occurs approximately 25 mm to 75 mm below the surface and in close proximity to the tire–pavement contact.

**IMPLEMENTATION OF THE MEPDG**

In the last decade, more states have adopted the MEPDG for design and rehabilitation of pavement structures. Although the MEPDG has a more theoretically grounded methodology for pavement analysis compared with traditional pavement design guides (e.g., the 1972, 1986, and 1993 AASHTO guides), it has several limitations and unrealistic simplifications that result in inaccurate response predictions. FE analysis is capable of overcoming these limitations and simulate pavement more accurately and realistically; however, it is computationally too expensive to adapt FE in the MEPDG framework. Therefore, the idea of developing adjustment factors was suggested to modify the MEPDG’s response to mend the gap between reality and the current flexible pavement simulation approach of the MEPDG (23).

Thus, the research approach of dividing the MEPDG limitations into two sets and developing an adjustment factor for each was introduced (23). The first set relates to the inability of the MEPDG to simulate WBT loading. The second set of limitations pertains to the pavement simulation complexities that are not considered in the MEPDG, such as three-dimensional nonuniform contact stresses, explicit viscoelastic characterization of AC, and nonlinear stress-dependent characterization of granular material. The approach is demonstrated in Figure 6.

The first part of this idea that accounts for the WBT effect on pavement response is presented in this study. The second part, considering the effect of model complexities on pavement responses, can be found elsewhere (23).

**CONCLUSION**

LET is the pavement analysis method used in the MEPDG. WBT loading cannot be simulated in the MEPDG because of the unrealistic assumptions and simplifications in implementing LET. Additionally, advanced structural techniques such as FE analysis are too computationally expensive to be used in the MEPDG. This paper suggests linear equations to quantitatively define the relationship between pavement responses under DTA and WBT loading. FE analysis is capable of simulating pavement–tire interaction more realistically in terms of material characterization and loading conditions was used to compute pavement responses. A total of 480 cases (240 for the DTA

**TABLE 3  Full List of Developed Equations for All Pavement Responses**

<table>
<thead>
<tr>
<th>Pavement Response</th>
<th>Location</th>
<th>Linear Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum tensile strain in traffic direction</td>
<td>AC surface</td>
<td>$WBT = 1.6 \times DTA - 2.0509$</td>
<td>.9939</td>
</tr>
<tr>
<td>Maximum tensile strain in transverse direction</td>
<td>AC surface</td>
<td>$WBT = 1.4039 \times DTA - 10.09$</td>
<td>.9657</td>
</tr>
<tr>
<td>Maximum tensile strain in traffic direction</td>
<td>Bottom of AC</td>
<td>$WBT = 1.2014 \times DTA + 4.3014$</td>
<td>.9867</td>
</tr>
<tr>
<td>Maximum tensile strain in transverse direction</td>
<td>Bottom of AC</td>
<td>$WBT = 1.5861 \times DTA - 4.92$</td>
<td>.9927</td>
</tr>
<tr>
<td>Maximum vertical compressive strain</td>
<td>Within AC</td>
<td>$WBT = 1.3689 \times DTA + 0.4778$</td>
<td>.9909</td>
</tr>
<tr>
<td>Maximum vertical compressive strain</td>
<td>Within base</td>
<td>$WBT = 1.1655 \times DTA + 1.2327$</td>
<td>.9944</td>
</tr>
<tr>
<td>Maximum vertical compressive strain</td>
<td>Within subgrade</td>
<td>$WBT = 1.1615 \times DTA - 4.5571$</td>
<td>.9898</td>
</tr>
<tr>
<td>Maximum vertical shear strain</td>
<td>Within AC</td>
<td>$WBT = 1.3873 \times DTA - 2.8506$</td>
<td>.9685</td>
</tr>
<tr>
<td>Maximum vertical shear strain</td>
<td>Within base</td>
<td>$WBT = 1.2077 \times DTA - 3.297$</td>
<td>.9944</td>
</tr>
<tr>
<td>Maximum vertical shear strain</td>
<td>Within subgrade</td>
<td>$WBT = 1.1113 \times DTA - 05281$</td>
<td>.9902</td>
</tr>
</tbody>
</table>

**FIGURE 6  AF approach (FEA = finite element analysis; $e$ = critical strain; $N$ = number of repetitions to failure; $f$ = empirical transfer functions).**

<table>
<thead>
<tr>
<th>Equation</th>
<th>$WBT$</th>
<th>$DTA$</th>
<th>$AF$</th>
<th>$ME$</th>
<th>$Design$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBT FEA</td>
<td>$WBT$</td>
<td>$DTA$</td>
<td>$AF$</td>
<td>$ME$</td>
<td>$Design$</td>
</tr>
<tr>
<td>DTA FEA</td>
<td>$DTA$</td>
<td>$WBT$</td>
<td>$AF$</td>
<td>$ME$</td>
<td>$Design$</td>
</tr>
<tr>
<td>DTA MEPDG</td>
<td>$DTA$</td>
<td>$ME$</td>
<td>$AF$</td>
<td>$Design$</td>
<td>$ME$</td>
</tr>
</tbody>
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demonstrated in Figure 6.
and 240 for WBTs) that aimed to capture extreme values for layer thickness, material characterization parameters, and load conditions were run in ABAQUS. Simulations that considered the same pavement structure and material properties were run for the DTA and for WBTs. The only difference was the applied contact loads that were measured for WBTs and the DTA under the same axle load and tire pressure. Validation of the developed equations was part of another study. Results of WBT and DTA responses in accelerated pavement tests will be used for validation of the introduced equations. The equations that were developed show that WBTs produced higher responses than did the DTA for all 10 critical pavement responses, which indicates higher damage to pavement. The highest effect of WBTs was the maximum tensile strain in transverse direction at the bottom of AC. On the other hand, the lowest effect of WBTs was observed for the maximum vertical shear strain within subgrade. Higher coefficient of determination values were observed when the axle load governed pavement behavior at increased pavement depths.

The developed equations create an opportunity for the MEPDG to consider WBT loading without the requirement of computationally expensive pavement analysis methods. It is recognized that implementation of these equations in the MEPDG may require recalibration of the transfer functions now used. The traffic composition and the number of axles per truck equipped with WBTs should also be considered in the pavement analysis, as should the fact that WBT market penetration in the United States is approximately 10%. The use of WBTs should also be evaluated in the comprehensive context of pavement-related, economic, and environmental impacts.

REFERENCES