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Impact of Wide-Base Tires on Pavements: A National Study

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Abstract

This paper summarizes a multi-year effort comparing the new-generation wide-base tires (NG-WBT) and dual-tire assembly from a holistic point of view. The tires were compared considering not only pavement damage but also environmental impact. Numerical modeling, prediction methods, experimental measurements, and life-cycle assessment were combined to provide recommendations about the use of NG-WBT. A finite element (FE) approach considering variables that are usually omitted in the conventional analysis of flexible pavement was used for modeling pavement structures combining layer thickness, material properties, tire load, tire-inflation pressure, and pavement type (interstate and low volume). A prediction tool, ICT-Wide, was developed based on an artificial neural network to obtain critical pavement responses in cases excluded from the FE analysis matrix. Based on the bottom-up fatigue cracking, permanent deformation, and international roughness index, the life-cycle energy consumption, cost, and green-house gas emissions were estimated. To make this research useful for state departments of transportation and practitioners, a modification to AASHTOware is proposed to account for NG-WBT. The revision is based on two adjustment factors, one accounting for the discrepancy between the AASHTOware approach and the FE model of this study, and the other addressing the impact of NG-WBT. Although greater pavement damage may result from NG-WBT, for the analyzed cases, the extra pavement damage may be outweighed by the environmental benefits when NG-WBT market penetration is considered.

Wide-base tires (WBT) provide numerous advantages compared with conventional dual-tire assembly (DTA). Regarding fuel economy, some studies indicate that fuel efficiency of WBT is 10% higher than that of DTA (*1,2*), or between 3.5 and 12% (*3*), and WBT can improve fuel economy up to 18% when combined with aerodynamic devices (*4*). In addition, WBT increases the hauling capacity of trucks by 2% because it is lighter than DTA (*5*); easier to inspect, repair, and maintain (*3*); uses less rubber material, so the amount of disposable materials at the end-of-life is diminished; has similar or slightly better performance than DTA with regard to handling and comfort (*5*); produces slightly less noise (*5*); and reduces emissions (*6*).

Despite its benefits, the impact of WBT on road infrastructure has been a concern for almost four decades since the inception of first-generation wide-base tires (FG-WBT) in the early 1980s. After FG-WBT were proved to be considerably more damaging to roads than conventional DTA (*7–12*), new-generation wide-base tires (NG-WBT) were introduced in an attempt to preserve the advantages of WBT while reducing pavement damage. The impact of NG-WBT on road infrastructure through accelerated pavement testing and experimental measurements (*13–20*) and analytical and numerical methods (*16,21*) has been studied; however, no evidence has been provided about their net benefit.

This study reflects a relevant step forward, where a comprehensive approach is used to compare NG-WBT with DTA. Numerical modeling, prediction methods, experimental measurements, and environmental impact assessment were combined to provide recommendations about the use of NG-WBT. Numerical modeling allowed the calculation of pavement responses based on an ample combination of variables, which incorporated accurate variables such as measured tire–pavement contact loads. A prediction tool based on an artificial neural network (ANN) was developed to obtain critical pavement responses in cases excluded from the finite element (FE) analysis matrix. The tool can promptly predict critical pavement responses without performing FE calculations. The experimental program aimed to validate the results of the numerical model and verify the trends inferred from the FE model for the scenarios of the testing program. The collected information was compiled in a database that users could access to retrieve experimental results. The environmental impacts were determined using life-cycle assessment (LCA) based on bottom-up fatigue cracking, permanent deformation, and international roughness index (IRI). LCA estimated life-cycle energy consumption, cost, and green-house gas (GHG) emissions. Finally, to make the outcome of this research effort readily implementable by state departments of transportation and practitioners, a modification to AASHTOware is proposed to account for NG-WBT. The revision is based on two adjustment factors, one accounting for the discrepancy between the AASHTOware approach and the FE model of this study, and the other addressing the impact of NG-WBT.

Tire–Pavement Contact Loads

The dual stress-in-motion (SIM) Mk IV system was used for contact load measurement (see Figure 1*a*). The system consists of two SIM pad assemblies; each pad consists of an array of 21 instrumented pins installed across the center portion of the assembly (*22*). The pins are instrumented with strain gauges, which are calibrated to convert strain to load. Static tire ink imprints were made using black roof paint on white paper under the HVS Mk III accelerated pavement testing system to obtain the contact area for each loading case.

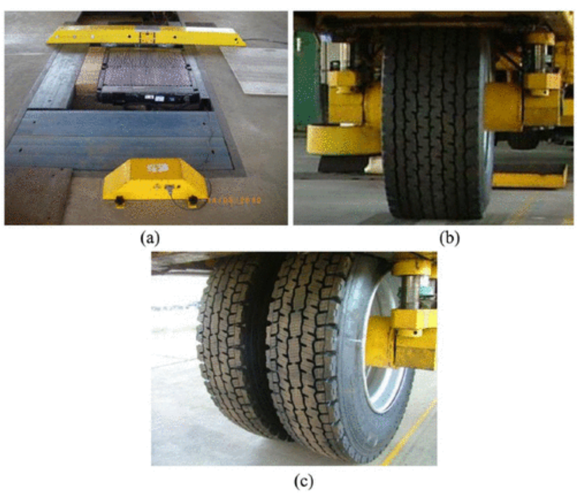

Figure 1. Tested tires and stress-in-motion system: (*a*) stress-in-motion systems; (*b*) new-generation wide-base tire 445/R22.4; (*c*) dual-tire assembly 275/80R22.5

Three-dimensional (3D) tire–pavement contact loads were measured for the NG-WBT 445/50 R22.5 and DTA 275/80 R22.5; the tires are presented in Figure 1, *b* and *c*. Four values of tire-inflation pressure S at 552, 690, 758, and 862 kPa, and five tire loadings P at 26.6, 35.6, 44.4, 62.3, and 80 kN, were applied to the tires to measure the 3D contact loads. In addition, differential tire-inflation pressure was considered for DTA; one tire of the assembly was kept at 758 kPa while two values, 413 and 552 kPa, were applied to the other.

Based on the measurements, peak forces per unit length in the vertical, longitudinal, and transverse directions are relatively higher for NG-WBT than DTA. In addition, regardless of the tire type, the magnitude of the tangential contact stresses is considerably high, which highly influences pavement responses. Although both tires have the same applied load and tire-inflation pressure, the ratios between the peak forces are different. Therefore, the effect of NG-WBT and DTA on pavement responses and performance cannot be assumed to be the same.

The contact area, obtained from static imprints, is also different for both tires. The contact area increased as the applied load reached 80 kN. Furthermore, the contact area was greater for DTA than NG-WBT for all loading cases, and the contact area ratio between DTA and NG-WBT was as high as 1.3. The average contact length for DTA was approximately 8% shorter than that for NG-WBT. Additional details regarding contact loads measurement and analysis can be found elsewhere (*23,24*).

Pavement Response and Damage

FE modeling was used to calculate critical pavement responses. The 3D model considers appropriate material characterization for each layer in the pavement structure and accurate representation of truck loading regarding direction, magnitude, and amplitude (*25*). The numerical predictions of critical pavement responses were contrasted with experimental measurements to ensure model validity (*26*). Various layer thicknesses for the asphalt concrete (AC) and base layers were combined to simulate low-volume and interstate roadways, termed as thin and thick pavements, respectively. Each pavement structure included two extreme values of thicknesses, in which the thin pavement simulated AC layer thicknesses of 75 and 125 mm, while the thick pavement considered three AC layers with total AC thicknesses of 125 and 412.5 mm. On the other hand, the granular base considered 150 and 600 mm layers. Regarding material property inputs, AC layers were assumed to be linear viscoelastic, while the base layer was assumed to be orthotropic stress-dependent (for thin pavement only) and linear elastic otherwise. Details of the material property selection can be found elsewhere (*25*).

Twelve loading cases were simulated to compare the impact of NG-WBT and DTA. As seen in Table 1, the load P was varied from 26.6 to 80.0 kN and the tire-inflation pressure S ranged from 552 to 862 kPa. Two DTA cases with differential tire-inflation pressures were included to represent realistic conditions in which the inner tire typically has a lower inflation pressure because of the difficulty of reaching the inner tire during maintenance.

Table 1. Simulated Loading Cases in Finite Element Analysis

Loading case	Tire	P (kN)	S (kPa)
L1	NG-WBT	26.6	552
L2	NG-WBT	26.6	862
L3	NG-WBT	80.0	552
L4	NG-WBT	80.0	862
L5	DTA	26.6	552
L6	DTA	26.6	862
L7	DTA	26.6	552/758
L8	DTA	80.0	552
L9	DTA	80.0	862
L10	DTA	80.0	552/758
L11	NG-WBT	44.4	758
L12	DTA	44.4	758

Trends were fairly similar when comparing pavement responses from NG-WBT and DTA with respect to various pavement layer thicknesses, material properties, and loading conditions. It was noticeable that NG-WBT produced higher critical pavement responses than DTA in most scenarios. In addition, the applied load governed the pavement responses more significantly than the tire-inflation pressure. Detailed comparison of the critical strains can be found elsewhere (*25*).

Transfer functions used by the mechanistic-empirical pavement design guide (MEPDG) were used to relate mechanistic strain responses to pavement damage by calculating the number of repetitions to failure. A ratio of the number of repetitions between the DTA and NG-WBT, DW, was calculated to compare the number of repetitions to failure of DTA, N_{DTA}, and the allowable number of repetition of NG-WBT, $N_{\mathrm{NG-WBT}}$. It is worth noting that $DW < 1$ indicates that the DTA has a lower number of allowable repetitions than NG-WBT.

$$DW = \frac{N_{\mathrm{DTA}}}{N_{\mathrm{NG-WBT}}}$$

Considering five pavement distresses, the cumulative impact of DTA relative to NG-WBT is compared using a combined ratio, CDW. All failure mechanisms considered are combined using a logarithmic weighing factor, a_i, to account for varying orders of magnitude among the number of repetitions to failure of each distress.

$$CDW = a_1 DW_{\mathrm{BU}} + a_2 DW_{\mathrm{TDS}} + a_3 DW_{\mathrm{TDT}} + a_4 DW_{\mathrm{RS}} + a_5 DW_{\mathrm{RH}}$$

$$a_i = \frac{\frac{1}{\log(N_i)}}{\sum_{j=1}^{5} \frac{1}{\log(N_j)}} \qquad (3)$$

where DW_{BU}, DW_{TDS}, DW_{TDT}, DW_{RS}, and DW_{RH} are the DW for bottom-up fatigue cracking, near-surface cracking caused by shear strain, near-surface cracking caused by tensile strain, subgrade rutting, and AC rutting, respectively. In the following plots, each group of bars corresponds to the same load and tire-inflation pressure. For instance, L6:L2 compares DTA and NG-WBT subjected to P = 26.6 kN and S = 862 kPa.

Thin Pavement Structures

The average damage ratios from the various material properties for thin pavements are shown in Figure 2. Lower damage for DW_{TDT} than other fatigue cases was noted; the average damage ratio for near-surface fatigue cracking caused by surface tensile strain was 1.28, while for bottom-up and near-surface caused by shear, the average damage ratios were 2.13 and 2.34, respectively (see Figure 2, *a*–*c*). For bottom-up fatigue cracking, DW_{BU} decreased as the magnitude of the applied load increased, and it was less sensitive to layer thickness when the load was high. On the other hand, DW_{TDS} increased as the load increased. For AC = 125 mm, average DW_{TDT} was not affected by base thickness, applied load, or tire-inflation pressure.

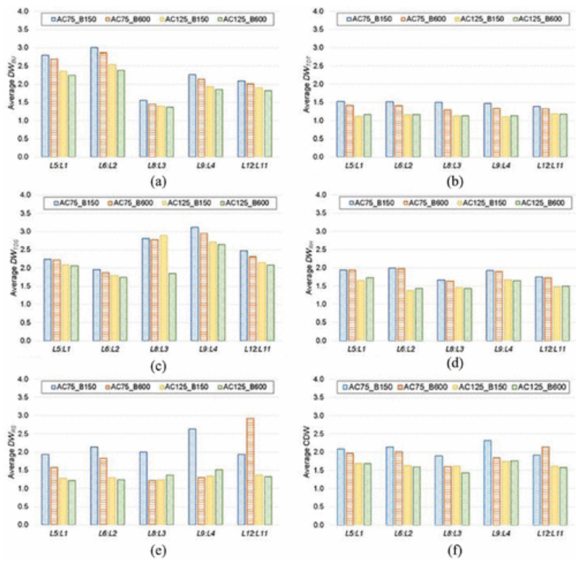

Figure 2. Ratio of the allowable number of repetitions to failure comparing DTA to NG-WBT for thin pavement structures: (a) DW for bottom-up cracking; (b) DW for top-down cracking due to tensile strain; (c) DW for top-down cracking due to shear strain; (d) DW for AC rutting; (e) DW for subgrade rutting; (f) CDW considering all five distresses.

Base thickness minimally affected the average difference between DW_{RH} of NG-WBT and DTA, as seen in Figure 2*d*. A more relevant role of tire-inflation pressure was observed for AC rutting when compared with fatigue cracking if the applied load was low and the AC thickness was 125 mm. On the other hand, tire-inflation pressure increased DW_{RH} when the applied load was high regardless of the layer thicknesses.

From Figure 2*e*, the average damage ratio for subgrade rutting indicated that if AC = 125 mm, the effect of base thickness was less significant than for AC=75 mm because the magnitude of vertical strain in the base layer is smaller for the thick AC layer. Also, the effect of tire-inflation pressure is more relevant in the case of AC = 75 mm because of the proximity of the subgrade to the loaded area. It should be noted that the average damage ratios for subgrade rutting are low compared with the other distresses. This agrees with the previous observation about the reduction in difference between NG-WBT and DTA as pavement depth increases. Combining all five pavement distresses, the highest average ratio was 2.4 for a load of 26.6 kN, tire-inflation pressure of 862 kPa, AC thickness of 75 mm, and base thickness of 150 mm. The average value in Figure 2*f* is 1.8, with the highest magnitude generally corresponding to pavement structures with thinnest AC. This suggests that the impact of NG-WBT could be significant on weak thin pavements.

Thick Pavement Structures

Based on Figure 3, DW_{BU} was highest at 3.2 when AC = 125 mm and B = 600 mm, although one could observe that the relative difference between the two tire types diminishes as AC thickness increases to 412.5 mm, regardless of the loading condition. Conversely, when considering the near-surface cracking caused by the surface tensile strain, DTA can impose between 0.4 to 4.6 times more loading repetitions than that of NG-WBT cases. Increasing the AC thickness to 412.5 mm (with B = 600 mm) generated the maximum DW_{TDT} of 4.6 when P = 26.6 kN. Although the range of average ratios significantly increased when P = 26.6 kN, the surface tensile strain difference between NG-WBT and DTA cases was less than 4 $\mu\varepsilon$. The resulting number of repetitions to failure were a magnitude different from the ones induced by near-surface shear strain and were much greater than 1.0^{10} repetitions when AC = 412.5 mm, which verifies that top-down cracking due to surface tensile strain is not the governing distress.

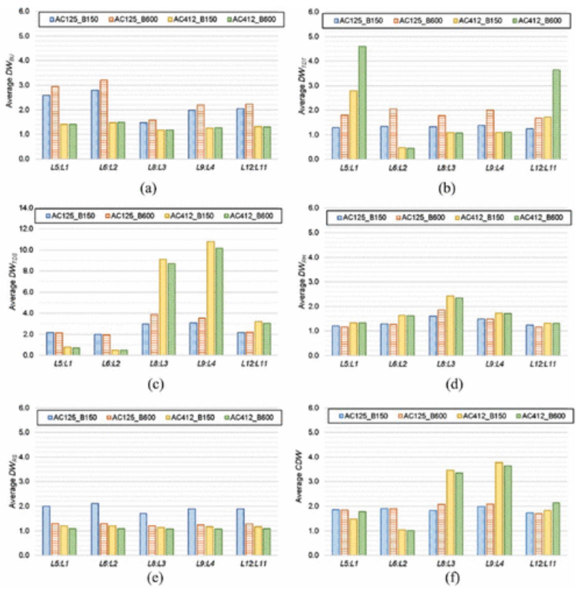

Figure 3. Ratio of the allowable number of repetitions to failure comparing DTA with NG-WBT for thick pavement structures: (a) DW for bottom-up cracking; (b) DW for top-down cracking due to tensile strain; (c) DW for top-down cracking due to shear strain; (d) DW for AC rutting; (e) DW for subgrade rutting; (f) CDW considering all five distresses.

On the other hand, DW_{TDS} significantly increased as the applied load became greater than 26.6 kN, as observed in Figure 3*c*. This increase was predominant when the AC layer was 412.5 mm thick and P = 80 kN, in which DW_{TDS} ranged from 8.7 to 10.8. One could infer that for thick pavements, the effect of the critical shear strain within the AC had a relatively high impact on near-surface damage, most especially under NG-WBT loading.

Based on Figure 3*d*, DW_{RH} were relatively low and resulted in values equal to or less than 1.5 for most cases, which indicates that the difference between DTA and NG-WBT is not as significant. However, under P = 80 kN and S = 862 kPa, DTA resulted in higher allowable repetitions than NG-WBT as DW_{RH} increased up to 2.4. Similarly, DW_{RS} ranged from 1.1 to 2.1, as seen in Figure 3*e*. Comparing the four pavement structures, DW_{RS} was the highest when AC = 125 mm and B = 150 mm, whereas the minimal difference between DTA and NG-WBT was observed for the remaining three thick pavement structures. Combining all the five distresses, the resulting CDW varied from 1.0 to 3.8 (Figure 3*f*). Consequently, for an applied load of 44.4 kN, the CDW remained relatively similar despite the change in pavement layer thickness, in which the ratios range from 1.7 to 2.1.

The damage induced by DTA with differential tire-inflation pressure (S = 552/758 kPa) and an applied load of 26.6 kN was higher than the DTA loading case subjected to 44.4 kN and uniform tire-inflation pressure of 758 kPa. The difference was higher for low-volume roads than for interstate highways. In general, the impact of NG-WBT is less on interstate highway structure than on low-volume roads.

Adjustment Factors

Although the MEPDG has a more theoretically grounded methodology for pavement analysis, as compared with traditional pavement design guides, it has several limitations and unrealistic simplifications that may result in inaccurate response predictions. These limitations and simplifications are mostly caused by the assumptions resulting from the use of multi-layered elastic theory (*27*). The FE model presented in this study can overcome these limitations by simulating tire–pavement interaction more realistically. However, it is computationally too expensive to adopt an FE model into the MEPDG framework. Therefore, two factors were created to adjust the pavement responses obtained from MEPDG in accordance with the developed FE model.

Adjustment Factor 2, AF2, adjusts the pavement responses obtained from MEPDG under DTA loading. The mechanistic part of the MEPDG procedure was implemented by exploiting the capabilities of Matlab and AutoHotkey. The main steps of implementing the MEPDG procedure are:

- Subdivision of pavement structure in sublayers
- Calculation of dynamic modulus at mid-depth of each sublayer
- Creation of input file
- Running JULEA (Linear Elastic Computer Program used by MEPDG)
- Post-processing to obtain pavement responses

Differences in loading conditions between FE and MEPDG (three-dimensionality and non-uniformity of the contact stresses), material characterization, and layer interaction introduce serious challenges that complicate the development of AF2. To obtain statistically good correlation for AF2, the cases were divided into three categories: (i) thick pavement, (ii) thin pavement with strong base material, and (iii) thin pavement with weak base material. A sample of AF2 is given for only two responses in Figure 4. Details about AF2 development and the results for all responses can be found in Gungor et al. (*27*).

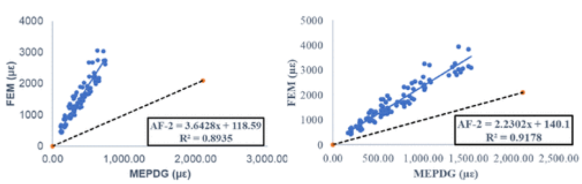

Figure 4. Maximum compressive strain within base for strong and weak base layers, respectively.

Adjustment Factor 1, AF1, was developed to convert the response resulting from DTA into NG-WBT because MEPDG cannot simulate NG-WBT. AF1 was created considering the same material properties and pavement structures. The only difference was the contact stresses and contact areas, which were measured under the same tire load for NG-WBT and DTA. AF1 is presented as a linear function of the DTA response, and a sample for two responses is provided in Figure 5. The full list of all the responses can be found in Gungor et al. (*28*).

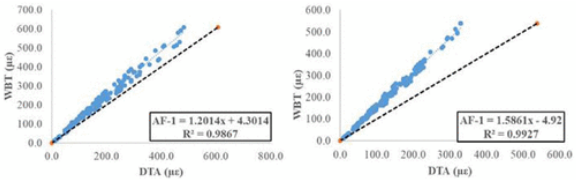

Figure 5. Maximum tensile strain at the bottom of the AC along the longitudinal and transverse direction, respectively.

Artificial Neural Network

ANN modeling was used as a prediction tool to estimate pavement responses because of the technical and computational challenges of calculating pavement responses for every possible combination of input variables using the FE method. In this study, multilayer perceptron (MLP) with Levenberg–Marquardt, a fast adoptive training algorithm, was used for training all models. The sigmoidal function was also utilized for the hidden layer. Details about the ANN methodology are well established in the literature and can be found elsewhere (*29,30*).

Given the cases simulated via FE method, ANN models interpolate the responses for any arbitrary case within the analysis matrix, for a fraction of a second relative to FE simulation time. Eleven responses, including longitudinal and transverse strains at surface and bottom of AC and vertical and shear strains in base and top of subgrade, were calculated. Critical variables affecting the responses, categorized as either loading or structure, were used as input. Detailed information regarding model development process and training results can be found elsewhere (*30*).

The material properties, especially complex modulus, are not readily available. Therefore, two levels of input properties were defined to account for data availability issues: Level 1 for detailed material properties and Level 2 for modulus of each layer at room temperature only. According to the results, the average error for all models was 4.0% with an *R*-squared value of 0.99, which indicates the high level of accuracy of ANN predictions. In addition, a *k*-fold cross-validation technique was used to test and obtain the optimum models. The lowest coefficient of correlation from all critical strains was 0.959 for the vertical strain in the AC of the thick pavement. In addition, the highest normalized root-mean-square error for thick pavement was 3.35% for the vertical shear in the subgrade.

A sensitivity analysis using two methods, the missing data problem and incremental sensitivity (also called one-at-a-time analysis), was implemented to analyze the ANN models (*29*). According to the sensitivity analysis, the pavement structure had the highest influence in both scenarios, and the tire type played an important role in pavement response calculation; in which a 10–30% influence on the response was found. This range of influence was nearly equal to the effect of tire-inflation pressure.

ICT-Wide Tool

To assist agencies, designers, and practitioners in the evaluation of the effect of NG-WBT on pavements, all trained models were incorporated into a tool called the Illinois Center for Transportation wide-base tool (ICT-Wide tool). The tool is a Matlab-based, stand-alone program that can be installed on any Windows operating system. The tool is capable of predicting critical responses of pavements as well as calculating damage to the pavement using both Mechanistic-Empirical and Asphalt Institute methods. Figure 6 shows the interface of the tool. For a 10% NG-WBT market penetration, the pavement impact increase could be outweighed by the environmental benefits.

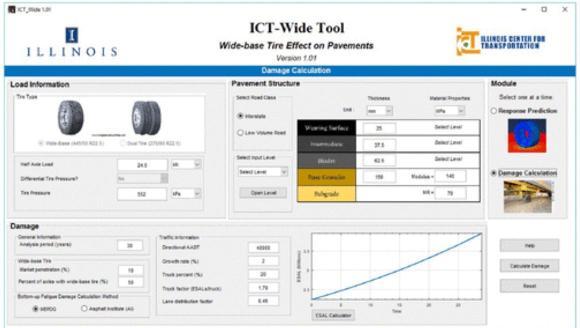

Figure 6. Main page of ICT-Wide tool.

Experimental Pavement Sections

Three new test sites were built and instrumented in Florida, California, and Ohio (*31*). Strain, stress, and temperature were measured at various locations within the pavement structures. The analysis of the experimental measurements showed 30% higher strain at the bottom of AC for NG-WBT. The impact of the applied load was different for each tire. Longitudinal strain at the bottom of the AC increased by 50% and 40% after changing the load from 26.7 to 80.0 kN for DTA and NG-WBT, respectively. Similarly, an increase in tire-inflation pressure from 552 to 827 kPa resulted in approximately 10% increase in strain at the bottom of AC for DTA and 20% for NG-WBT. For the same change in tire-inflation pressure, surface transverse strains augmented 30% and 40% for DTA and NG-WBT were measured, respectively.

The research team also gathered pavement responses from previous projects that used NG-WBT. Existing and new data were compiled and organized in an online database that could be made available to the public. The online database was developed to organize data and utilize both new and existing data, considering NG-WBT loading on pavements. The database management procedure included pre-processing data, filtering and smoothing, max/min response extraction, post-processing and summary, and online application design.

Life-Cycle Assessment and Life-Cycle Costing

The use of NG-WBT can improve the fuel efficiency of trucks by 1–3.5% (*3*), but at the same time it could cause a greater impact on pavement. Therefore, a holistic study considering the entire life-cycle of a pavement is needed to properly assess the net environmental benefit of NG-WBT compared with DTA.

This study used LCA, a technique that compiles and evaluates inputs and outputs (i.e., environmental impacts) of a product system during its life-cycle (*32*). Goal and scope definition, methodology, and key assumptions regarding the LCA study are described in detail elsewhere (*33*). Relevant pavement life-cycle stages considered are material, construction, and use-stage (rolling resistance [RR] due to roughness and fuel savings from NG-WBT) of AC overlay. The result of the LCA study is annualized and the functional unit used is two-mile-two-lane-year. The study also considered different levels of NG-WBT market penetration (5, 10, 50, and 100%); 0% market penetration implies 100% DTA and is considered as the baseline. Two pavement sections with different AC overlay thicknesses (75 mm and 125 mm) were also considered; the pavement sections share the same base and subgrade layers, consisting of 250 mm milled and recompacted base, 320 mm old aggregate base, 200 mm tipped and compacted subgrade on top of clayey subgrade.

Based on the scenario-based case study, the net energy saving for each life-cycle stage by using different levels of NG-WBT market penetration is calculated and shown in Figure 7. The three scenarios considered are as follows: (i) Scenario I: standard DTA and NG-WBT; (ii) Scenario II: DTA and NG-WBT have the same IRI performance but different fatigue cracking potential; and (iii) Scenario III: DTA and NG-WBT have the same fatigue cracking potential but different IRI performance. Details of the models used to conduct the case study are described in Kang et al. (*33*). It is evident in most cases of this particular case study that the use of NG-WBT brings positive life-cycle environmental savings compared with DTA, even if additional pavement damage is considered. The only exception is with the thin AC overlay section of Scenario III, in which increased burdens in material and construction stages, and RR surpassed the savings from NG-WBT at high market penetrations.

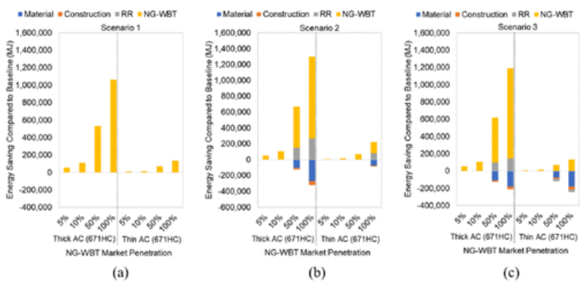

Figure 7. Net energy saving of using NG-WBT for (*a*) Scenario I, (*b*) Scenario II, and (*c*) Scenario III (*33*).

For Scenario I, the net life-cycle costing benefits were positive; those for Scenarios II and III were slightly negative at certain market penetrations (50 and 100%) for the thick section (*33*). However, environmental and economic benefits are sensitive to the method used to determine the pavement performance.

Summary and Conclusions

The main objective of this study was to present a multi-year effort that compared the impact of NG-WBT and DTA on pavements and environment. Contact loads of the NG-WBT and DTA were measured and incorporated in a numerical model to realistically simulate pavement structures, materials, and loading conditions. The model was validated with various field test sections across the United States. Good agreement was noted between FE analysis results and field-instrumented pavement responses when using proper material characterization parameters, especially for vertical pressure and tensile strain at the bottom of AC in transverse direction.

It was evident that NG-WBT responses were generally greater than DTA for pavements. The difference decreased with depth and a few cases showed higher responses for DTA (e.g., shear strain in the subgrade in thin pavement). In addition, DTA with differential tire-inflation pressure produced higher damage than DTA with the same tire-inflation pressure when compared with the tire with the highest tire-inflation pressure. As expected, different behavior was observed for low-volume (thin) and interstate roads (thick). On one hand, for low-volume roads, subgrade rutting was the controlling distress of the pavement life; the difference between the impacts of the two tires on subgrade failure was minimal. For interstate highways, the influence of NG-WBT was greater than that of DTA, in which the controlling distress in AC was top-down or near-surface cracking and possible AC rutting.

Since MEPDG may not be used directly for predicting responses of NG-WBT, two adjustment factors were developed to modify the pavement responses obtained from MEPDG to account for model complexity and different contact mechanisms of DTA and NG-WBT. Furthermore, to simplify the process of using NG-WBT and allow for implementation by agencies, an ANN tool was developed to predict the pavement response without running FE. The tool results rendered by the ANN surrogate models were highly accurate, with an average prediction error less than 5% and R-square values higher than 0.95. It was also observed that although NG-WBT could cause greater pavement response than DTA for some roads, NG-WBT demonstrated significant improvement compared with the FG-WBT.

From the environmental point of view and based on LCA models that considered NG-WBT market penetration percentages, NG-WBT could save energy and reduce GHG and emissions, depending on corresponding pavement performance. Based on the results of the study and using the developed tools, for a NG-WBT market penetration of 10%, the pavement impact increase could be outweighed by the environmental benefits as well as cost savings in energy.

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