

# STATE OF FLORIDA



## **IMPACT OF WIDE-BASE SINGLE TIRES ON PAVEMENT DAMAGE**

Research Report

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**STATE MATERIALS OFFICE**

## TABLE OF CONTENTS

Table of Contents .....	i
List of Figures .....	i
List of Tables .....	i
Executive Summary .....	1
Introduction .....	2
Wide-Base Tires .....	2
Pavement Damage Potential .....	3
Research Objectives .....	3
Experiment Design .....	4
Permanent Deformation through Accelerated Pavement Testing .....	5
Surface Strain Investigation .....	7
Finite Element Analysis .....	8
Impact on Florida Roadways .....	12
Acknowledgements .....	14
Disclaimer .....	14
References .....	15

## LIST OF FIGURES

FIGURE 1 Photograph of tire used in the study .....	3
FIGURE 2 Pavement structure .....	4
FIGURE 3 Rut depth summary .....	6
FIGURE 4 Typical dual tire strain profile at 8 mph (13 kph) .....	7
FIGURE 5 Surface transverse strain measurement on dense graded surface .....	8
FIGURE 6 Pavement structure and model for FE analysis .....	9
FIGURE 7 Tire geometry and contact pressure used in FE analysis .....	10
FIGURE 8 Predicted stress distributions .....	11
FIGURE 9 2008 Pavement Condition Survey Summary .....	13

## LIST OF TABLES

TABLE 1 Tire Contact Area .....	9
TABLE 2 Summary of Predicted Strains .....	12

## EXECUTIVE SUMMARY

Dual tires have traditionally been used to limit pavement damage by efficiently distributing axle loads over a larger contact area than single tires. However, in recent years the trucking industry has promoted the use of wide-base single tires stating economical and safety benefits. The Super Single tire, an early type of wide-base tire, proved inadequate and induced excessive pavement damage. In contrast, the new generation wide-base tires have contact areas that approach those of dual tires and offer the potential for improved performance.

The Florida Department of Transportation (FDOT) investigated the pavement damage potential of four tire types including a conventional dual tire (11R22.5), a Super Single (425/65R22.5), and two newly-designed wide-base single tires (445/50R22.5 and 455/55R22.5, respectively). A controlled accelerated pavement testing program in addition to theoretical modeling was performed to determine critical pavement response parameters. Pavement damage was measured in terms of rutting and fatigue cracking (bottom-up or top-down), the predominant distresses in Florida. The investigation revealed the 455-mm wide-base tire performed as well as the dual tire. In comparison, the 445-mm wide-base tire was shown to create more rut damage on a dense-graded pavement surface and was also predicted to create more bottom-up cracking than a dual tire. As expected, the Super Single induced the most damage to the pavement.

This paper presents a description of the test program, the data collection efforts, and the subsequent analysis and findings.

## INTRODUCTION

There have been a number of innovations in tire technology to address the evolving needs of the trucking industry for efficiency. Recently, a new generation of wide-base tires with greater tread widths has been introduced. These tire developments directly impact pavement damage. Pavement damage from tires can be controlled by adequately distributing the load over a larger area of the pavement surface to minimize critical stresses and strains. Dual tires have traditionally provided the largest footprint to adequately distribute the axle load onto the pavement surface. As the name implies, wide-base single tires provide a wider footprint than conventional single tires and attempt to distribute the load over a contact area similar to that of standard dual tires. The first generation of wide-base tires (385/65R22.5 and 425/65R22.5) was introduced in the early 1980's (1). These tires ultimately proved to cause an increase in pavement contact stress and in turn generated even greater pavement damage (2). A new generation of wide-base (NGWB) tires (445/50R22.5 and 455/55R22.5) became available after 2000 (1). The trucking industry has encouraged their use due to their increased pavement contact area, and promise of economical and safety benefits. However, potential pavement damage induced by NGWB tires must be assessed before the wholesale adoption of their use.

## WIDE-BASE TIRES

The trucking industry is encouraging the use of NGWB tires due to the perceived economic, safety, and environmental benefits. Of primary interest to many trucking organizations is the potential of cost savings. Most combination trucks use dual tire assemblies on the drive and trailer axles. Rolling resistance accounts for nearly 13 percent of truck energy use. A single wide-base tire is lighter than two standard tires and wheels. A single wide-base tire, as opposed to a standard dual tire configuration, would reduce weight and rolling resistance (3). A typical weight savings of a combination truck that replaces five axles of dual tires with single wide-base tires ranges from 800 to 1,000 pounds (360 to 450 kg) (3, 4). The American Trucking Association (ATA) reported potential fuel savings as a result of the improved rolling resistance and reduced weight range on average from 2 to 3 percent and possibly up to 8 percent (4). An Environmental Protection Agency (EPA) study showed reduction in fuel use of 6 percent at 55 mph (90 kph), 12 percent at 65 mph (105 kph), and 10 percent in a suburban environment (5).

Load and pressure must be balanced on dual tire configurations, but it is often difficult to monitor the inner tire due to its location. Wide-base tires only have one outside valve and can be visually checked for low pressure. Furthermore, wide-base tires provide a lower center of gravity and have been reported to improve ride quality (4).

In addition to increasing fuel efficiency, wide-base tires have been promoted to reduce vehicle emissions which are related to engine power output. Therefore, reductions in power requirements due to improved efficiency should also result in a decrease in emissions, particularly for emissions of oxides of nitrogen (NOx) as opposed to particulate matter. An EPA study measured NOx emission reductions of 36 percent at 55 mph (89 kph), 30 percent at 65 mph (105 kph), and 13 percent in a suburban environment (5). Finally, NGWB tires appear to generate less scrap since they contain less sidewall area compared to dual tires (4).

It should be noted that there are potential disadvantages to the use of wide-base tires as well. It appears that tread wear may be increased for local and urban operations. The ATA has reported that miles to removal have decreased 25 to 35 percent for NGWB tires as compared to duals and there have also been reports of increased retread failure rates which may result in vehicle damage (4). Also, two sets of wheel hardware must be maintained until all trucks in a fleet are converted to wide-base tires.

## PAVEMENT DAMAGE POTENTIAL

There are two primary failure mechanisms observed on flexible pavements in Florida. These failure mechanisms include permanent deformation (rutting) and fatigue cracking of the hot mix asphalt structure. Many models, including the Mechanistic-Empirical Pavement Design Guide (MEPDG), recognize that permanent deformation may take place in both bound and unbound layers, and that fatigue cracking can initiate from the bottom or top of an asphalt layer. However, permanent deformation of the base is uncommon in Florida pavements while the top-down cracking is a prevalent distress on Florida roadways.

Recent studies have shown that NGWB tires generate similar rut depths as dual tires but induce greater longitudinal strains at the bottom of the asphalt layer which will accelerate bottom-up fatigue cracking damage (6, 7, 8, 9). Furthermore, NGWB tires often generated similar or less surface shear strains than dual tires (6, 7, 8, 9). The first generation wide-base tires, often referred to as Super Singles, were shown to clearly decrease the tire contact area and, therefore, increase the pavement contact stresses. The increase in vertical and lateral stresses induced by the Super Single tires significantly increased the likelihood of top-down cracking and near-surface rutting of asphalt pavements (2).

## RESEARCH OBJECTIVES

As previously stated, the primary objective of this research was to assess the impact on pavement performance of different tire designs including (1) a conventional dual tire configuration, (2) two types of NGWB tires, and (3) a first generation wide-base tire. The four tire systems are described below:

1. Goodyear Unisteel G149 RSA, 11R22.5 (Dual Tire)
2. Goodyear G286 A SS, 425/65R22.5 (Super Single)
3. Michelin X One XDA-HT Plus, 445/50R22.5 (NGWB 445-mm)
4. Michelin X One XDA-HT Plus, 455/55R22.5 (NGWB 455-mm)



**FIGURE 1** Photograph of tire used in the study.

To allow for a faster and a more practical assessment under closely simulated in-service conditions, accelerated pavement testing (APT) was considered to address the objectives of this study. APT is generally defined as a controlled application of a realistic wheel loading to a pavement system simulating long-term, in-service loading conditions. This allows the monitoring of a pavement system's performance and response to accumulation of damage within a much shorter time frame. In Florida's APT program, the accelerated loading is performed using a Heavy Vehicle Simulator (HVS), Mark IV model. The HVS is electrically powered (using an external electric power source or electricity from an on-board diesel

generator), fully automated, and mobile. A complete description of the test facility has been presented elsewhere (10, 11). The APT empirical approach was also supplemented by rigorous theoretical procedures to further quantify the critical pavement response parameters.

## EXPERIMENT DESIGN

In order to better understand the pavement damage induced by each tire, several aspects of the tire and pavement interaction were investigated. As part of the APT portion of this study, a total of six test lanes (numbered 2 through 7) were constructed considering both open and dense-graded asphalt surface textures while complying with all the standard FDOT construction, materials, and in-place (as constructed) methods and specifications. For all pavement test sections, the supporting layers consisted of a 10.5 inch limerock base over a 12 inch limerock stabilized subgrade. Two different pavement structures, comprised of three asphalt mixtures, were tested. The asphalt mixtures consisted namely of (1) a fine-graded Superpave with a 12.5-mm nominal aggregate size and a PG67-22 binder (SP-12.5), (2) a fine-graded friction course mixture with a 12.5-mm nominal aggregate size and a binder with 5 percent asphalt rubber (FC-12.5), and (3) an open-graded friction course mixture and a binder with 12 percent asphalt rubber (FC-5). The SP-12.5 and FC-12.5 mixtures were similar with the exception of the binder type. The pavement structures are shown in FIGURE 2. Each test lane was divided into three pavement sections (identified as A, B and C), with each pavement section being approximately 50 feet (15.2-m) long and 12 feet (3.7-m) wide. In order to account for construction variability, the order of test sections and tire types were randomly selected. At least three replicate tests were conducted for each tire and pavement structure combination.

Open-Grade Surface Lanes 2, 3, and 4	Dense-Grade Surface Lanes 5, 6, and 7
0.75 inch (19-mm) FC-5, ARB-12	2 inch (50-mm) FC-12.5, ARB-5 93% Gmm
2 inch (50-mm) SP-12.5, PG 67-22, 93% Gmm	3.5 inch (89-mm) Existing SP-12.5
3.5 inch (89-mm) Existing SP-12.5	10.5 inch (265-mm) Limerock Base Course
10.5 inch (265-mm) Limerock Base Course	12 inch (305-mm) Granular Subbase
12 inch (305-mm) Granular Subbase	12 inch (305-mm) Granular Subbase

Note: ARB-12 represents 12% asphalt rubber binder.

**FIGURE 2 Pavement structure.**

Accelerated loading was performed uni-directionally with a 5 inch (127-mm) wheel wander in 1 inch (25-mm) increments. The reasoning for such a loading configuration was provided elsewhere (10). All tires except for the Super Single were inflated to 100 psi (689 kPa). The recommended inflation pressure for the Super Single tire is 115 psi (772 kPa). A 9,000 pound (40 kN) load was applied to all wheels at a speed of 8 mph (13 kph). The temperature was held constant at 122 ° F (50° C) by installing insulated panels and employing a heater system integrated into the HVS. Each lane was trafficked until a rut depth of approximately 0.50 inch (12.5-mm) was measured. Trafficking of some lanes was discontinued before reaching a 0.5 inch (12.5-mm) rut depth if the rate of rutting appeared to be constant.

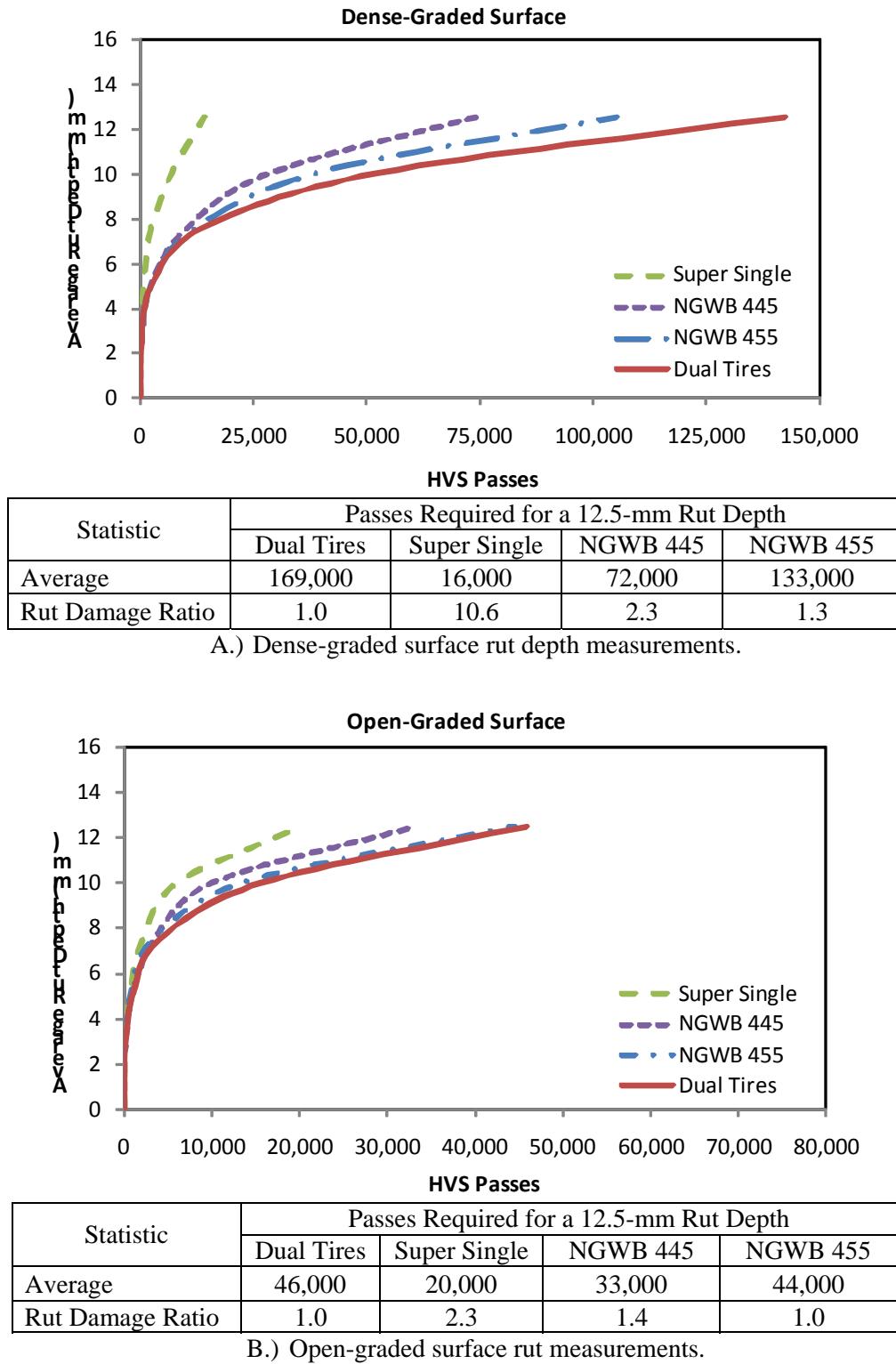
Lane 1, which was constructed similarly as Lanes 2 though 4, was used to measure surface strain caused by each tire. Finally, the dense-graded pavement structure and tire interaction was modeled using finite element analysis (FEA) to determine the theoretical pavement response to the different tires. Loaded tire geometry and contact area was measured to determine a more accurate modeling approach.

## **PERMANENT DEFORMATION THROUGH ACCELERATED PAVEMENT TESTING**

For both pavement types, the dual tire configuration allowed a greater number of passes before reaching the critical rut depth while the Super Single tire resulted in the least number of passes. In general, the NGWB 455-mm tire required a similar number of passes on the open-graded surface and slightly less for the dense-graded surface (when considering the variability in tests) as compared to the dual tires. The NGWB 445-mm tire reached the critical rut depth with less passes than the dual for both surface types, particularly for the dense-graded surface. The Super Single tire reached the critical rut depth with significantly less number of passes than the duals for both asphalt mixtures.

FIGURE 3 reports the rut depth and the rut damage ratio. The rut damage ratio is simply the ratio of the average number of passes required for a standard tire (in this case, the dual tires) to that of the other respective tires tested to achieve an approximate rut depth of 0.5 inch (12.5-mm).

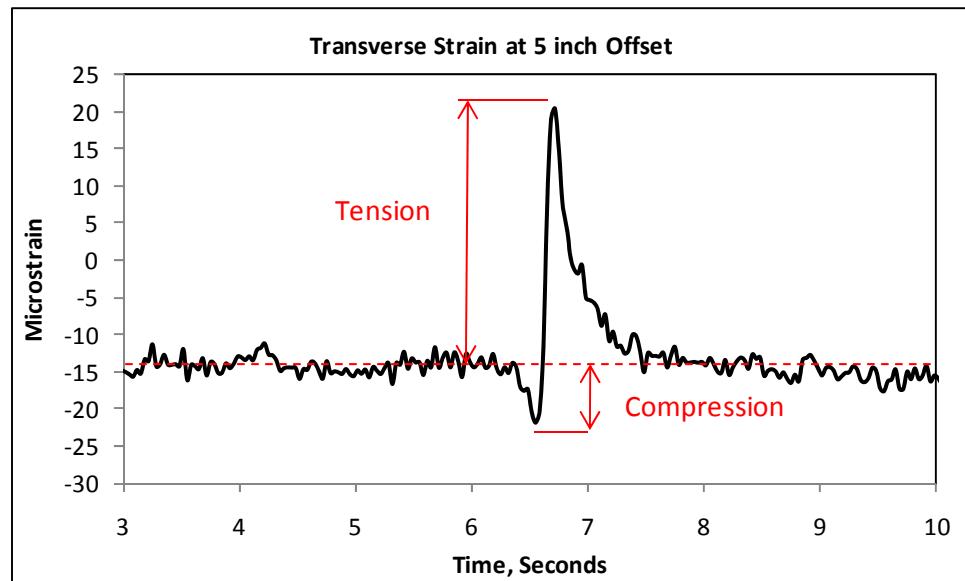
It is believed that the large difference in rate of rutting between the dense-graded pavement and open-graded pavement is likely due to the lower modulus of the open-graded friction course and effects from the accelerated nature of the test. While not measured in this study, literature indicates that the modulus of an open-graded pavement is approximately 50 to 80 percent lower than conventional dense-graded mixtures (12). Furthermore, a previous FDOT funded study showed that open-graded friction courses tend to rut faster during accelerated testing than typically observed in the field (13). This study indicated that the open-graded aggregate structure was not allowed time to stabilize due to the increased loading frequency and shortened evaluation period during testing with the asphalt pavement analyzer.

**FIGURE 3 Rut depth summary.**

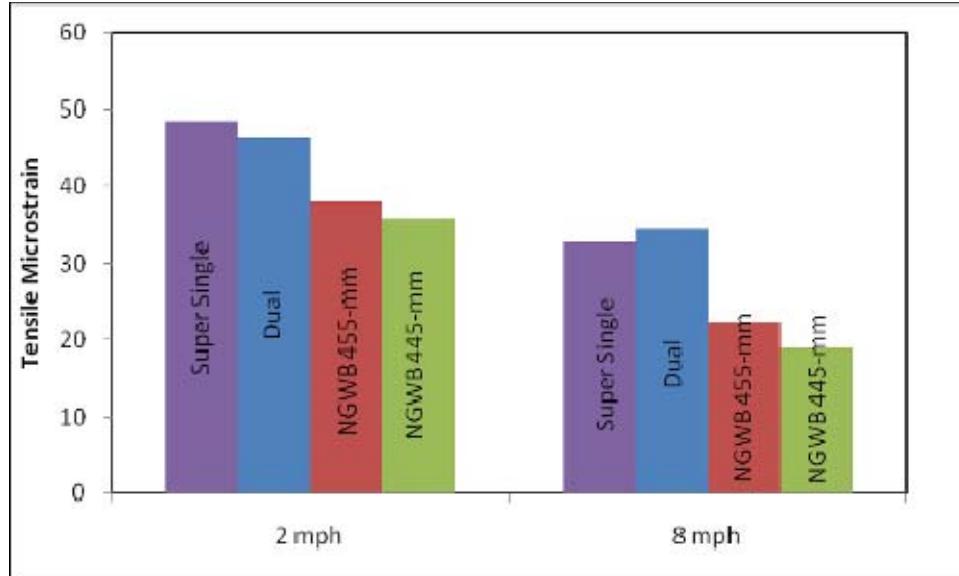
## SURFACE STRAIN INVESTIGATION

Top-down cracking is one of the primary distresses observed on Florida pavements. Top-down cracks are thought to form due to tensile and shear stresses generated by repeated loading in combination with stiffness gradients from aging and thermal effects. In order to determine the potential for top-down cracking, tensile strain measurements were made on the dense-graded surfaced pavement. Two transverse 1.2 inch (30-mm) foil surface strain gauges were placed 5 inches (127-mm) from the tire edge, a location where it was thought tensile strain would dominate. Five HVS wheel passes were made with each tire at 2 mph (3 kph) and 7 mph (11 kph). Strain measurements were not corrected for temperature, since the pavement surface temperature at the time of testing was  $78 \pm 2^\circ \text{F}$  for all tire and speed combinations.

A representative strain profile made 5 inches (127-mm) from the dual tire edge is shown in FIGURE 4. In general, the strain measurements exhibited slight compressive strain as the wheel approached the gauge and tensile strain and reversal as the wheel moved away from the gauge. The strain magnitudes for each tire and speed are shown in FIGURE 5. The dual and Super Single generated the greatest transverse strain. As expected, transverse strain was reduced when the speed increased. While the magnitudes of measured strain are not likely to induce top-down cracking on a new pavement, these strains may be enough to generate cracks on older pavements subjected to aging and repeated loading. Additionally, some researchers suggest that load location in combination with asphalt stiffness gradients are critical to crack propagation (14).



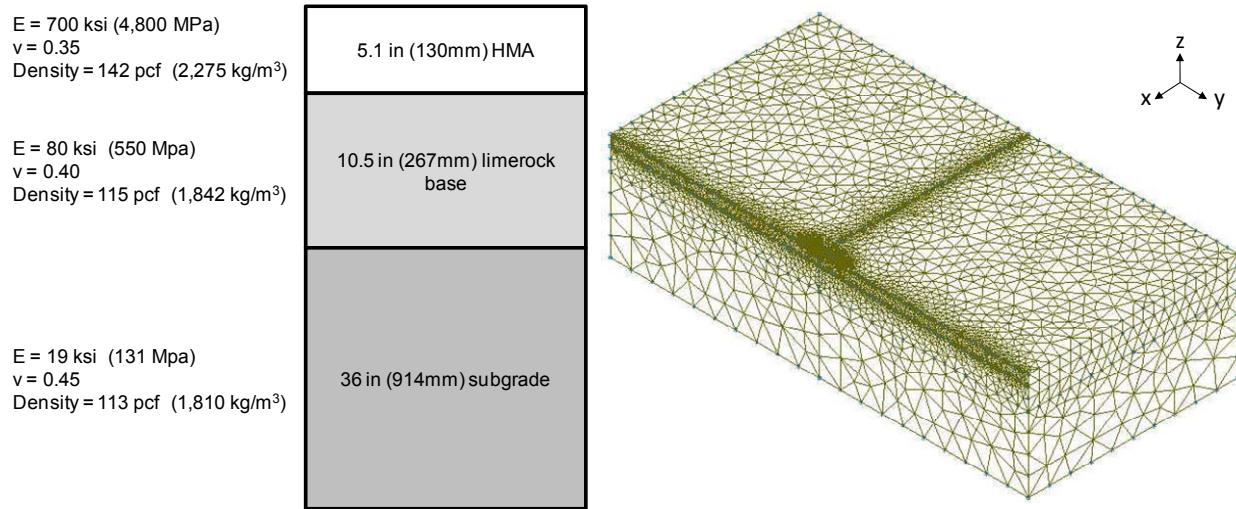
**FIGURE 4** Typical dual tire strain profile at 8 mph (13 kph).



**FIGURE 5 Surface transverse strain measurement on dense graded surface.**

## FINITE ELEMENT ANALYSIS

The commercial software ADINA was used for finite element (FE) modeling of the pavement structure and tire loads. In general, a finer mesh is recommended for more detailed results. However, it is not always preferable if computation times and storage capacity become excessive. Therefore, to reduce the number of elements for a 3D model without compromising the analysis, a symmetrical geometry about the x-axis (perpendicular to the wheel path) was used. To minimize the effect of boundary conditions, the model dimensions were 200 inches (5080-mm) wide by 100 inches (2540-mm) in length. A 3D element with 10 nodes was used as the element type. A finer mesh at the center of the y-axis near the loaded area and the x-axis was achieved by the Delaunay technique. A relatively coarser mesh was used at the boundaries. Fixed support was used along the z-axis at the bottom of the subgrade layer and the x-axis along the model boundary. The modeled pavement structure was based on the dense-graded surfaced section. Material properties were determined through nondestructive deflection and seismic testing as well as laboratory analysis. The open-graded surface was not modeled since it was difficult to accurately measure the properties of the FC-5 with a falling weight deflectometer or other nondestructive means. The pavement structure and corresponding model are shown in FIGURE 6.

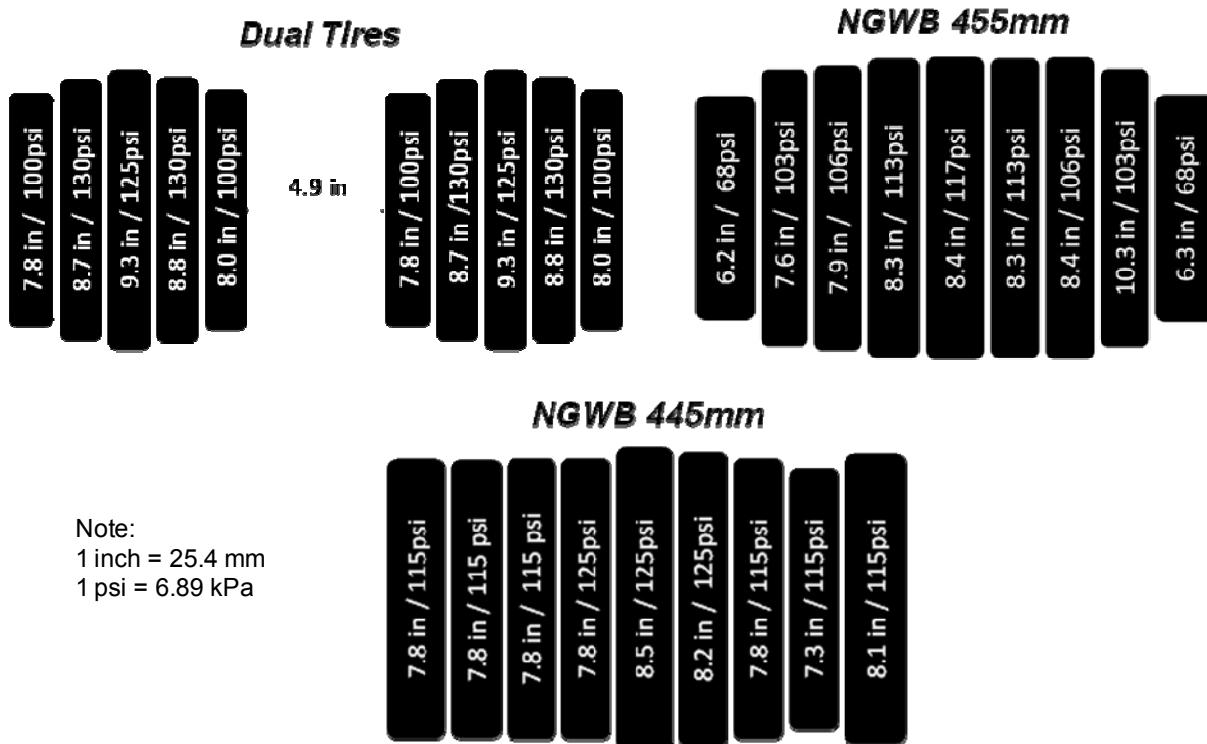
**FIGURE 6 Pavement structure and model for FE analysis.**

In order to more accurately model the true tire contact area, the imprint of each tire tread was measured at the recommended inflation pressure. Each imprint was converted into a digital image and pixels were counted and converted to an area measurement using an imaging software application. TABLE 1 summarizes the tire contact areas measured at various inflation pressures and loads. In general, the contact area decreased for a given load as the inflation pressure was increased. Conversely, the tire contact area increased for a given inflation pressure as the load was increased. Due to the high lateral stiffness of the tire, the tread width remained relatively constant (1.3 to 1.7 inches or 33 to 43-mm) while the length increased with increasing load and decreasing inflation pressure. Diagrams of the modeled geometry and contact pressure are shown in FIGURE 7. Tread contact pressures for the dual tire, NGWB 455 mm, and NGWB 445 mm were taken from a study by Al-Qadi et. al (15). The Super Single tire was not modeled since accurate contact pressure was not available.

**TABLE 1 Tire Contact Area**

Tire	Inflation Pressure, psi	Measured Contact Area, square inch			
		9 kip	12 kip	15 kip	18 kip
Dual	80	124	150	173	174
Dual	100	119	145	165	NA
Dual	125	103	133	152	NA
Super Single	80	97	120	138	142
Super Single	115	75	103	116	137
Super Single	125	77	96	120	137
NGWB 445	80	100	121	140	NA
NGWB 445	100	101	125	138	NA
NGWB 445	125	82	108	129	142
NGWB 455	80	113	135	153	NA
NGWB 455	100	96	114	140	NA
NGWB 455	125	81	114	122	142

Note: 1 inch =  $6.45 \text{ cm}^2$   
1 kip = 4.45 kN  
1 psi = 6.89 kPa



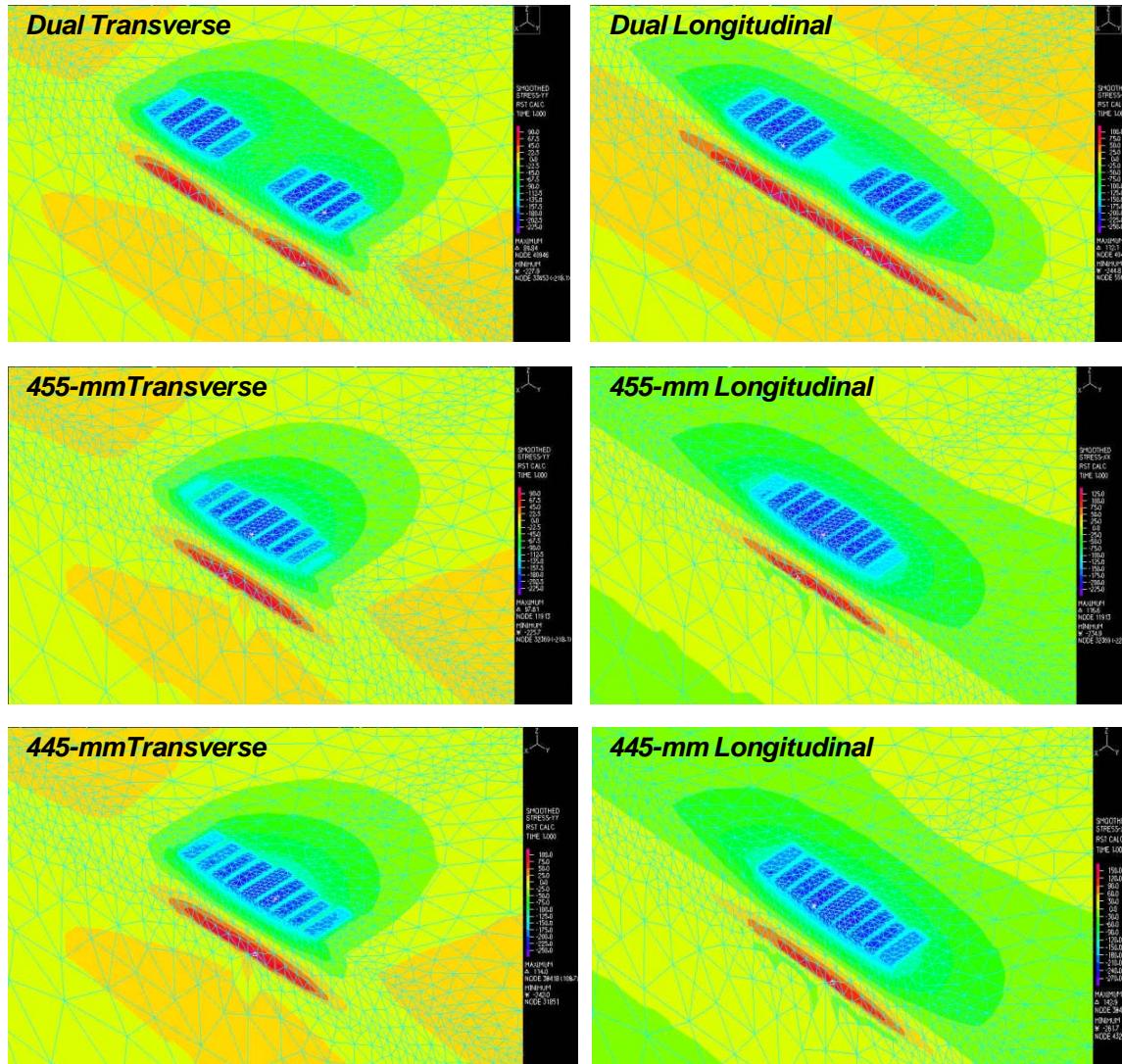
**FIGURE 7 Tire geometry and contact pressure used in FE analysis.**

The following four parameters were investigated using the FE model and analysis:

1. Vertical strain in the asphalt layer to indicate rutting potential.
2. Horizontal surface strain to indicate top-down cracking potential.
3. Shear strain below the tire edge to indicate top-down cracking potential.
4. Horizontal tensile strain at the bottom of the asphalt layer to indicate bottom-up fatigue cracking potential.

The stress distributions along the symmetrical transverse face for each tire are shown in FIGURE 8. As expected, the greatest tensile stress was predicted at the bottom of asphalt layer (shown in red) even with non-uniform tire pressures. On the pavement surface, the greatest compressive stress occurred below the tire treads. . A more detailed description of each investigated parameter is included in the following paragraphs.

Vertical tensile stresses developed near the surface due to lateral compressive stresses induced by the treads. The dual tire induced a greater tensile stress at the surface between the tires due to a more dominant effect from shear stresses. As found in the FE models reviewed in the literature, similar vertical compressive strains were predicted for each of the modeled tires. However, the 445-mm wide-base tire produced rut damage much quicker than the 455-mm and dual tires for the dense-graded pavement surface in the APT experiment. This indicates that a simple elastic model may not provide an accurate method to evaluate rutting potential. Viscoelastic parameters, loading frequency, and deformation accumulation should be accounted for as well.



**FIGURE 8 Predicted stress distributions.**

Top-down cracking in Florida is primarily observed as longitudinal cracks inside or just outside the wheel path. As with the measured surface strains presented earlier, the dual tire was predicted to induce the greatest surface strain. The maximum transverse tensile strain was predicted to occur approximately 9 to 10 inches (230-mm to 255-mm) from the tire edge regardless of tire type. The magnitudes of the predicted strain were smaller than those measured. However, the predicted strain values and predicted locations of maximum tensile strain were not necessarily expected to match since a greater load was used in the HVS experiments. A recent FDOT study also indicated that the maximum surface strain would occur approximately 10 inches (250-mm) from the tire edge (16). The 455-mm wide-base tire was predicted to generate the least amount of shear strain below the tire edge. The dual and the 445-mm wide-base tire generated similar shear strains. The maximum shear strain for all of the tires was determined to occur at a depth of approximately 2 inches. However, the shear strains at shallower depths were still greater than the surface tensile strain. The actual critical location for top-down cracking found

on in-service pavements most likely corresponds to a combination of critical shear and tensile stresses due to tire induced stresses, environmental aging effects, and other surface distresses such as rutting.

Tensile strain measured at the bottom of the asphalt was used to indicate bottom-up fatigue cracking potential. The NGWB 445-mm tire was predicted to induce slightly more tensile strain and create more bottom-up fatigue cracking damage. The NGWB 455-mm tire and the dual tire produced similar tensile strains and could be expected to produce similar bottom-up fatigue crack damage. TABLE 2 summarizes the FE model predicted strains

**TABLE 2 Summary of Predicted Strains**

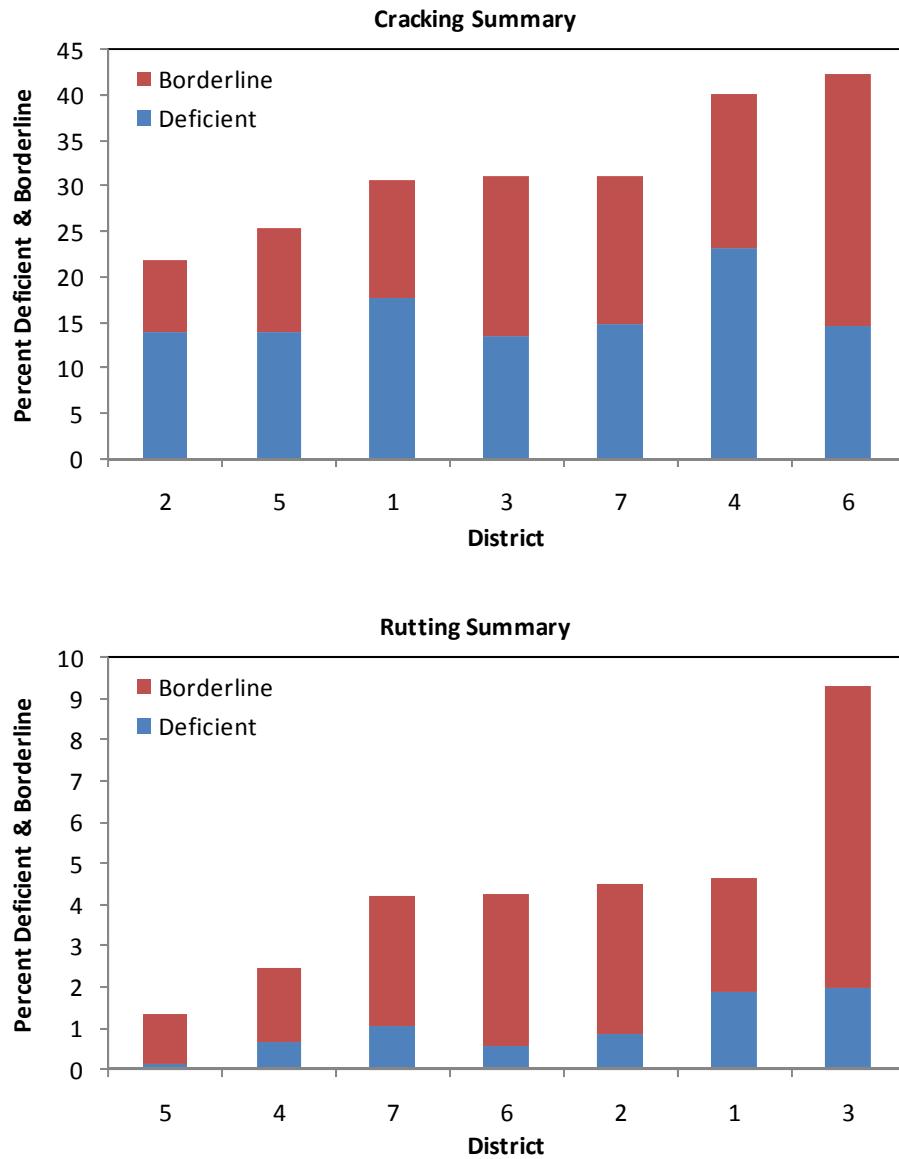
Tire Type	Maximum Predicted Strain, Microstrain			Strain Ratios				
	Rutting	Top-Down Cracking		Bottom -Up Cracking	Rutting	Top-Down Cracking		Bottom- Up Cracking
	Compressive Strain	Transverse Strain	Shear Strain	Tensile Strain	Compressive Strain	Transverse Strain	Shear Strain	Tensile Strain
Dual	353	31	180	162	1.0	1.0	1.0	1.0
NGWB 455	373	28	139	156	1.1	0.9	0.8	1.0
NGWB 445	390	24	178	187	1.1	0.8	1.0	1.2

## IMPACT ON FLORIDA ROADWAYS

Dual tires have been predominantly used on Florida roadways. Pavement damage on Florida roadways is documented through annual surveys conducted by the State Materials Office (SMO). Crack and rut damage is determined on a scale of 1 to 10, with 10 representing a pavement with no damage. A rating of 6 or less indicates a deficient pavement that is eligible for rehabilitation. A rating of 7 may be considered borderline deficient. In 2008, more than 30,000 miles were surveyed statewide. A summary of the 2008 survey is shown in FIGURE 9 (17). Cracking is the predominant distress and in general, is more widespread in South Florida (Districts 4 and 6). Rutting is more common in the Panhandle (District 3).

Based on the results of this study, the pavement damage induced by the 455-mm wide-base tire could be considered similar to that of the dual tire in terms of rutting and bottom-up cracking and slightly improved in terms of top-down cracking. On the contrary, the 445-mm tire was shown to rut dense-graded pavement surfaces more than twice as fast as a standard dual. The 445-mm tire was also predicted to create slightly more bottom-up cracking damage than a dual tire, but less or similar surface cracking damage. The pavement damage trends shown in 2008, particularly rutting damage on dense-graded surfaces, would likely increase if the 445-mm tire is included in the future.

This research is important to FDOT and the trucking industry. It is important that new technology be thoroughly evaluated in terms of cost benefit and performance to both the transportation industry and the highway infrastructure where it will be applied. This research showed that by increasing the tire contact area, pavement damage can be decreased.



**FIGURE 9 2008 Pavement Condition Survey Summary.**

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**DISCLAIMER**

The content of this paper reflects the views of the authors who are solely responsible for the facts and accuracy of the data as well as for the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Florida Department of Transportation. This paper does not constitute a standard, specification, or regulation. In addition, the above listed agency assumes no liability for its contents or use thereof.

## REFERENCES

1. Al-Qadi, I.L., and M.A. Elseifi. New Generation of Wide-Base Tire and Its Impact on Trucking Operations, Environment, and Pavements. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 2008, Transportation Research Board of the National Academies, Washington D.C., 2007, pp.100-109.
2. Myers, L. A., R. Roque, B. E. Ruth, and C. Drakos. Measurement of Contact Stresses for Different Truck Tire Types to Evaluate Their Influence on Near Surface Cracking and Rutting. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1655, Transportation Research Board of the National Academies, Washington D.C., 1999, pp.175-184.
3. A Glance at Clean Freight Strategies: Single Wide-Based Tires EPA Technical Bulletin 420-F-04-004. <http://www.epa.gov/smartway/transport/documents/tech/supersingles.pdf>. Accessed April 15, 2009.
4. Routhier, Brian. Wide-Base Tires Fleet Experiences. Presented at the International Workshop on the Use of Wide-Base Tires, Federal Highway Administration Turner-Fairbank Highway Research Center, 2007.
5. Bachman, L. J., A. Erb, and C. L. Bynum. Effect of Single Wide Tires and Trailer Aerodynamics on Fuel Economy and NOx Emissions of Class 8 Line-Haul Tractor-Trailers. Presented at the 2005 Society of Automotive Engineers Commercial Vehicle Engineering Conference, Detroit, Michigan, 2005.
6. Dessouky, S. H., Al-Qadi, I. L., and Yoo, P. J. Full-Depth Pavement Response to Different Truck Tire Loadings. Presented at the 86th Transportation Research Board Annual Meeting, Washington D.C., 2007.
7. Dore, Buy. Laval University's Experience with Wide-Base Single Tires. Presented at the International Workshop on the Use of Wide-Base Tires, Federal Highway Administration Turner-Fairbank Highway Research Center, 2007.
8. Timm, D.H., and A.L. Priest. Mechanistic Comparison of Wide-Base Single Versus Standard Dual Tire Configurations. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1949, Transportation Research Board of the National Academies, Washington D.C., 2006, pp.151-163.
9. Elseifi, M.A., I.L. Al-Qadi, P.Y. Yoo, and I. Janajreh. Quantification of Pavement Damage Caused by Dual and Wide-Base Tires. In *Transportation Research Record, Journal of the Transportation Research Board*, No. 1940, Transportation Research Board of the National Academies, Washington D.C., 2005, pp.125-135.
10. Byron, T., B. Choubane, and M. Tia. *Assessing Appropriate Loading Configuration in Accelerated Pavement Testing*. Proceedings, 2<sup>nd</sup> International Conference on Accelerated Pavement Testing, Minneapolis, MN, 2004.
11. Choubane, B. S. Gokhale, G. Sholar, and H. Moseley. Evaluation of Coarse and Fine-Graded Superpave Mixtures Under Accelerated Pavement Testing. In *Transportation Research Record: Journal of the Transportation Research Board*, No 1974, National Research Council, Washington D.C., 2005, pp. 120-127.
12. Roque, R., C. Koh, Y. Chen, X. Sun, and G. Lopp. *Introduction of Fracture Resistance to the Design and Evaluation of Open Graded Friction Courses in Florida*. Report BD545-33, Florida Department of Transportation, 2009.
13. Birgisson, B, R. Roque, A. Varadhan, T. Thai, and L. Jaiswal. *Evaluation of Thick Open Graded and Bonded Friction Courses for Florida*. Report BC354-81, Florida Department of Transportation, 2006.
14. Birgisson, B., J. Wang, and R. Roque. *Implementation of the Florida Cracking Model Into the Mechanistic Empirical Pavement Design*. Report BD545-20, Florida Department of Transportation, 2006.

15. Al-Qadi, I.L., C.E. Via, M. Elseifi, and P.J. Yoo. *Pavement Damage Due to Different Tires and Vehicle Configurations*. Final Report Submitted to Michelin Americas Research and Development Corporation. Virginia Tech Transportation Institute, 2004.
16. Kim, Jaeseung, T. Byron, G. Sholar, and S. Kim. Comparison of a Three-Dimensional Viscoelastic Pavement Model with Full-Scale Field Tests. Presented at 87<sup>th</sup> Annual Meeting of the Transportation Research Record, Journal of the Transportation Research Board, Washington D.C, 2008.
17. 2008 Flexible Pavement Condition Survey Facts and Figures. FL/DOT/SMO/08-518, <http://materials.dot.state.fl.us/SMO/administration/resources/library/publications/researchreports/pavement/08-518.pdf>, Accessed June 1, 2008.