NCAT Report 05-03

MECHANISTIC COMPARISON OF WIDE-BASE SINGLE VS. STANDARD DUAL TIRE CONFIGURATIONS

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DISCLAIMER

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MECHANISTIC COMPARISON OF WIDE-BASE SINGLE VS. STANDARD DUAL TIRE CONFIGURATIONS

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INTRODUCTION

As commercial trucking has evolved, there have been many developments in tire technology, and now tires are available in a variety of sizes, treads, load capacity, and inflation pressures. The fairly recent evolution of commercial tires has produced progressively wider tires that replace the standard dual tire configuration with a single tire. The standard axle consists of four tires (two on each side) with each tire having a tread width of approximately 8.75 inches (222 mm). The new axle configuration consists of two wide-base tires (one on each side) with a footprint of up to 17.5 inches (444.5 mm) wide. These axles are typically paired in a tandem axle group. Figure 1 shows the contrast in size between the standard tire and the wide-base tire. The wide-base single tire, sometimes known as a super single tire, is more commonly used in Europe. For example, as of 1997, wide-base singles comprised 30 percent of the tires in France and Britain compared to 2 percent in the U.S. (Abdo, 2004).

Figure 1. Standard Dual Tire and Wide-base Single Tire.

There are many different types of wide-base tires available in varying sizes and inflation pressures. In addition to simply enlarging the size of the tire, there have been recent developments in tread and load-bearing technology that allow for lower inflation pressures and even greater surface area than the initial wide-base tires that were introduced in the early 1980s. Although wide-base tires can offer benefits like increased cargo capacity, there are legitimate concerns that they may cause premature distress to the highway infrastructure. Wide-base tires have struck the interest of trucking and tire industries as well as highway agencies and pavement engineers since their introduction over 20 years ago.

Background

The trucking industry is continually developing new and innovative ideas to increase efficiency through tire, suspension, and engine developments. The focus of this study is recent tire development. Historically, tires have come in a variety of sizes with different dimensions and inflation pressures. The nomenclature of tires includes three tire dimensions and type of tire in the form of AAA/BBXCC.C. The first number (AAA) is the tire width from wall-to-wall in millimeters, the second number (BB) is the side wall height given as a percent of the tire width, the letter (X) indicates the type of tire, and the third number (CC.C) is the tire rim diameter in inches. For example, a tire with designation 275/80R22.5 is a radial tire (indicated with the 'R') with a wall-to-wall width of 275 mm, a wall height of 220 mm, and a rim diameter of 22.5 in. The naming scheme is standardized and uniform among manufacturers. As a result, the classification offers much useful information.

As mentioned, there have been many developments in the trucking industry in attempt to increase industry efficiency. The new generation of wide-base tires is one such development, and offers many benefits. The wide-base tire assembly decreases gross vehicle weight by 880-1,272 lbs (allowing more cargo weight), increases fuel economy by 2-5 percent, and lowers tire repair and replacement costs (Kilcarr, 2001; "Wide-base," 2002). However, there are also safety issues concerning blowouts with a single tire axle. Unlike the standard dual tire configuration, if a tire blows out in the single configuration, there is not a paired tire to temporarily carry the load while the driver brings the vehicle to a controlled stop. Although on a limited scale, wide-base tires are currently being manufactured and used in the U.S., and much of the trucking and tire industries continue to push for the widespread acceptance and use of wide-base tires.

In contrast, a general concern has been raised by State and Federal transportation agencies regarding the impact of the tires on pavement performance. The wide-base single configuration lowers the total contact area of the tires on the pavement, increasing the stress applied to the roadway. Further, they are conventionally run at higher inflation pressures, which may cause more surface damage. Although there may be economic benefits to the trucking industry, they should be balanced against the impact on the transportation infrastructure and overall effect on the consumer.

To address this concern, the Federal Highway Administration (FHWA) initiated a study in 1989 to investigate the effect of wide-base single tires, specifically the 425/65R22.5, on flexible pavement response and performance at the Accelerated Loading Facility at the Turner-Fairbanks Research Center. This study found that measured pavement strain and stress significantly increased under the single wide-base tires, and both the fatigue and rutting life of the pavement decreased dramatically (Bonaquist, 1992). Other studies using computer models found similar results. For example, a study conducted by Siddharthan et al. (1998) used a newly developed continuum-based finite-layer model with dynamic loading to investigate the effect of wide-base singles. This study found that the wide-base tire (the same tire that was used at FHWA) caused a 33 and 16 percent increase in calculated strain under a 6 in. and 10 in. asphalt layer, respectively. Both studies focused on the induced strain at the bottom of the asphalt layer because that particular pavement response is linked to fatigue damage and is used in pavement thickness design. Based on conclusions of such studies, many agencies placed restrictions on the use of wide-base or single tires to preserve the integrity of their highway infrastructure (Al-Qadi et al., 2005).

As mentioned prior, there have been recent developments in wide-base tire technology. The most current wide-base singles have a much wider tread width and a lower profile than those developed in the 1980s. Further, they carry the load differently than their predecessors and are designed to be run at higher speeds and lower tire inflation pressures (Kilcarr, 2001). The new tires are designed to reduce pavement damage by decreasing the tire-pavement surface stress and provide a more uniform surface contact pressure (Al-Qadi et al., 2005). More recent studies of these tires have shown that there is not a significant difference in pavement response at the surface or within the layers between a standard dual tire assembly and a wide-base single. In 2004, a study was conducted using both finite-element (FE) analysis and instrumented field test sections at the Virginia Smart Road on two new generation wide-base tires, the 445/50R22.5 and 455/55R22.5 (Al-Qadi et al., 2005). Fatigue cracking, top-down cracking, and rutting failure mechanisms were considered. The study concluded that the larger of the two, the 455/55R22.5, induced approximately the same pavement response or damage as the standard dual assembly tested (275/80R22.5). The other wide-base tire tested (445/50R22.5) was found to slightly increase the induced damage, and small load restrictions were suggested when using these tires.

Because of the continued development of new and improved tires, it should not be concluded that all wide-base tires will increase pavement distress. Rather, continued research and investigation into the immediate and prolonged effects of tires as they are developed is needed. This includes analysis through mechanical models, measured pavement response, and field performance.

This study investigated the commercially available 445/50R22.5 wide-base tire. This particular tire represents some of the most recent improvements in tire technology, and it is one of the widest available tires on the market. In addition, the manufacturer developed this tire to improve the stress distribution at the contact surface to create a more uniform load along with increasing the contact width and size to distribute the load over a larger area. Measured pavement response, including strain and stress measurements, were made in the field using instrumented pavement test sections. In addition, a theoretical analysis was conducted to compute pavement response using layered elastic analysis. The theoretical analysis was a critical part of the study because further investigation is warranted into how wide-base tires are modeled. For example, is it accurate to model a wide-base tire in a similar manner as conventional tires with simply a different loaded area? It is important to assess the accuracy (or deficiency) of theoretical models in predicting response under wide-base tires before they are used extensively to evaluate newly-developed single tires. Because this study included both the theoretical and the measured pavement response components, the two could be compared and analyzed.

Objectives

Based on the issues presented above, a study was conducted at the National Center for Asphalt Technology (NCAT) Test Track with the following goals:

1. Model the two tire configurations and predict the pavement response and effect of the wide-base tire using a layered elastic computer model.
2. Measure and compare the field dynamic pavement response of the two tire configurations.
3. Evaluate the effectiveness of the computer model in predicting the pavement response for both tire configurations.

Scope

To accomplish the above objectives, the standard dual tire currently used on the test vehicles at the NCAT Test Track (275/80R22.5) and a newly developed single wide-base tire (445/50R22.5) were compared through predicted and measured pavement responses. The two tire configurations, single wide-base and standard dual, are shown together in Figure 2. The NCAT Test Track, shown in Figure 3, is an ideal location to make such a comparison because the instrumented test sections, including strain and pressure gauges, can measure the dynamic response of the pavement under a moving load. Field testing was conducted at one test section over two days in October, 2004. In addition to the measured pavement response, an investigation was conducted using a layered elastic theoretical model. The specifics and results from both testing schemes are discussed in detail.

Figure 2. Wide-Base Single (445/50R22.5) and Standard Dual (275/80R22.5) Tires.

THEORETICAL ANALYSIS

Prior to field testing, simulations were run using a linear layered elastic program to predict the strain and stress in the pavement structure under load. Both tire assemblies were simulated using the computer model to serve as an early prediction and reality check. In other words, the results from layered elastic analysis gave an indication of what could be expected in the field. In addition, the results from this analysis were compared to the field analysis as an indication of the accuracy of the theoretical models. It was not the objective of this study to extensively develop or evaluate a sophisticated computer program to model wide-base singles, but instead, to use a readily available and relatively simple program to get an initial prediction that could later be compared to the measured field response. It is important to note that linear layered elastic models are the current state-of-the-practice for both pavement analysis and design, and are therefore an appropriate model to evaluate.

Figure 3. NCAT Test Track.

The analysis program used in this study to predict the pavement response and corresponding predicted performance under the two loading conditions was WESLEA for Windows. The analysis program has been evaluated with field traffic response data and shown to be reasonably accurate (Chadbourn et al., 1997). The program was initially developed through Waterways Experiment Station (WES) and uses linear layered elastic theory to calculate stress and strain at specified locations in the pavement structure under circular tire loads. The program was used here to calculate the response at three critical locations in the pavement structure corresponding to gauge locations in the actual test section. Then, the predicted responses were compared to the measured field responses to judge the accuracy of the program in evaluating the effect of wide-base tires on pavement response.

Methodology

Within the program, both the pavement structure and the applied load must be defined. Care was taken to include the most specific and exact information in both areas.

The cross-section and material properties of field test section N5 were first modeled in WESLEA. The most recent and accurate information was used including the as-built surveyed pavement thickness and the unbound material properties from the most recent backcalculated falling weight deflectometer (FWD) data. Because the hot-mix layer properties are very dependant on temperature, the modulus was taken from the temperature-moduli relationship established from months of backcalculated data based on the mid-depth asphalt temperature during testing. The pavement structure and material properties of the test section are shown in Figure 4. It should be noted that the backcalculation analysis of the test sections has proven most accurate when the 6 in. granular base and 17 in. compacted subgrade are considered as one 23 in. layer, as shown in the figure.

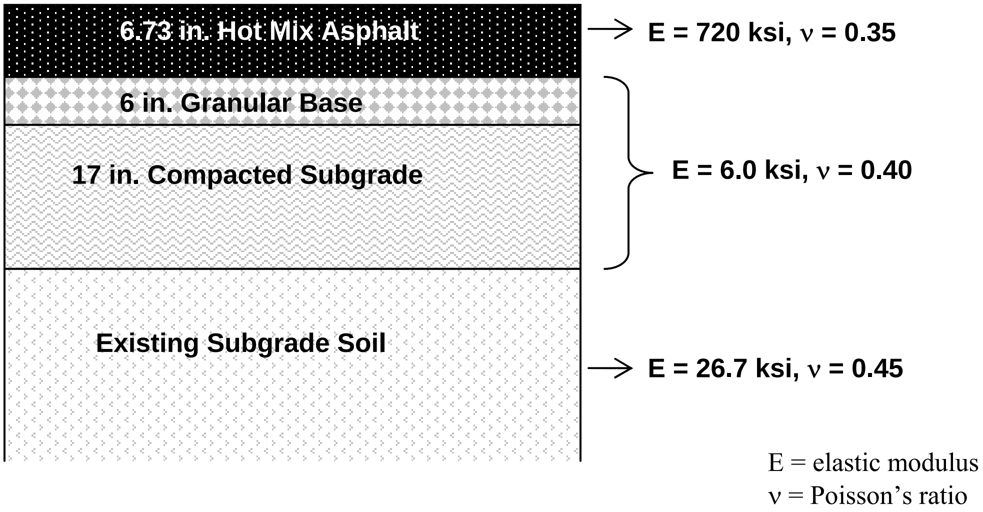

Figure 4. Cross Section of Test Section N5.

The applied load in WESLEA is characterized by the tire configuration, load per tire, and tire inflation pressure. These inputs are then used to define a circular loaded area of uniform pressure in the specified load configuration. To obtain the required inputs, measurements were taken from the test vehicle.

The test vehicle, shown in Figure 5, was a legally-loaded semi-trailer, and the test axle was the rear tandem axle circled in the figure. The axle weights were measured with portable scales to determine the exact distribution of the vehicle weight, and the included tire pressures were the inflation pressures during testing. Figure 6 illustrates the weight distribution. The rear tandem carried a total of 34,200 lbs, which was distributed unevenly between the front and rear axles of the rear tandem group. Therefore, the dual tire configuration was defined as a standard tandem axle with a single tire load of 4,637.5 lbs in the front and 3,912.5 lbs for the back tires with an inflation pressure of 100 psi. The single tire tandem assembly was modeled with a tire load of 9,275 lbs and 7,825 lbs in the front and back axles, respectively, with 120 psi tire inflation pressure.

Figure 5. NCAT Test Vehicle.

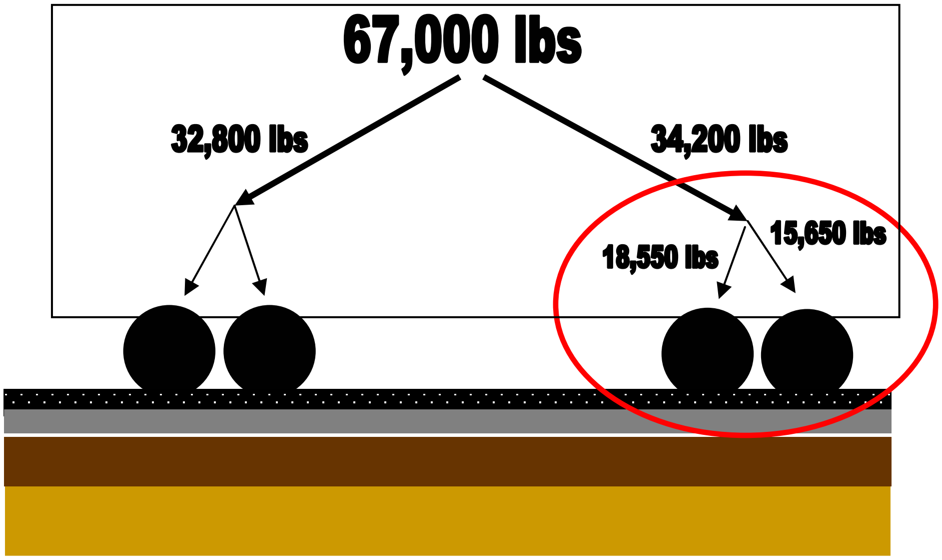

Figure 6. Test Vehicle Weight Distribution.

Results and Discussion

Historically, there are two pavement responses that are considered the most critical to asphalt pavement performance. It is widely accepted that excessive horizontal tensile strain at the bottom of the asphalt layer and vertical pressure at the top of the base (or subgrade) lead to fatigue cracking and structural rutting, respectively (Monismith, 1992). Therefore, these pavement responses were calculated using WESLEA to compare the effects of the two tire configurations for the pavement structure previously defined. These locations and measurements were also important because they each corresponded to a gauge location and measurement in the field test section.

The calculated responses are shown in Figures 7 and 8, and in all instances, the calculated stress or strain significantly increased under the wide-base tire. Of the three reported measurements, the horizontal tensile strain (Figure 7) was the most severely affected by the single tire configuration. WESLEA predicted an increase in strain of about 46 percent, which will greatly accelerate fatigue cracking and impact the pavement performance. Additionally, the vertical stress on the base and subgrade layers also increased by 25 and 11 percent, respectively, and the higher induced stress could lead to reduced rutting performance.

The increase in pavement response measurements presented from linear layered elastic theory were expected considering that the single tire configuration was carrying the same load as the dual tire configuration over a smaller contact area. As mentioned above, WESLEA models the tire load by calculating a circular tire imprint given the load and the inflation pressure. Therefore, the axle load of 18,550 lbs was carried over four tires with a total calculated surface area of 185.5 in^2 for the dual tire axle and over two tires with a total surface area of 154.6in^2 for the single tire axle, a decrease of 17 percent.

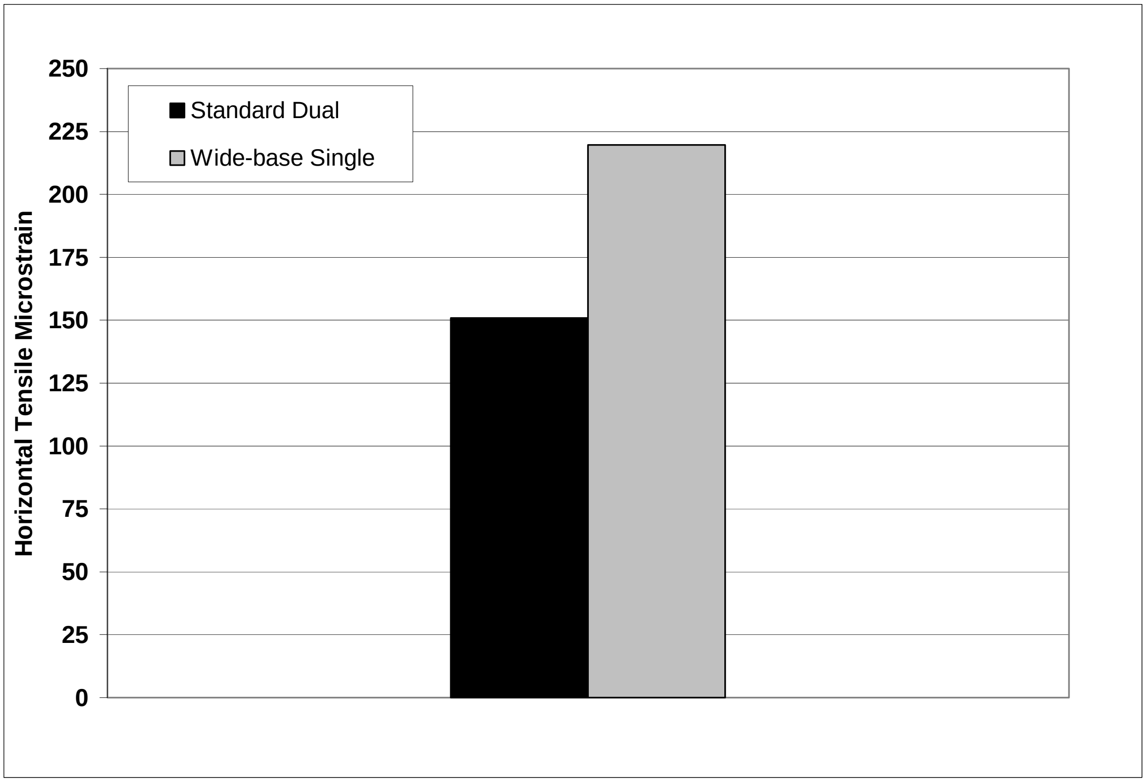

Figure 7. Calculated Horizontal Strain at the Bottom of the Asphalt Layer.

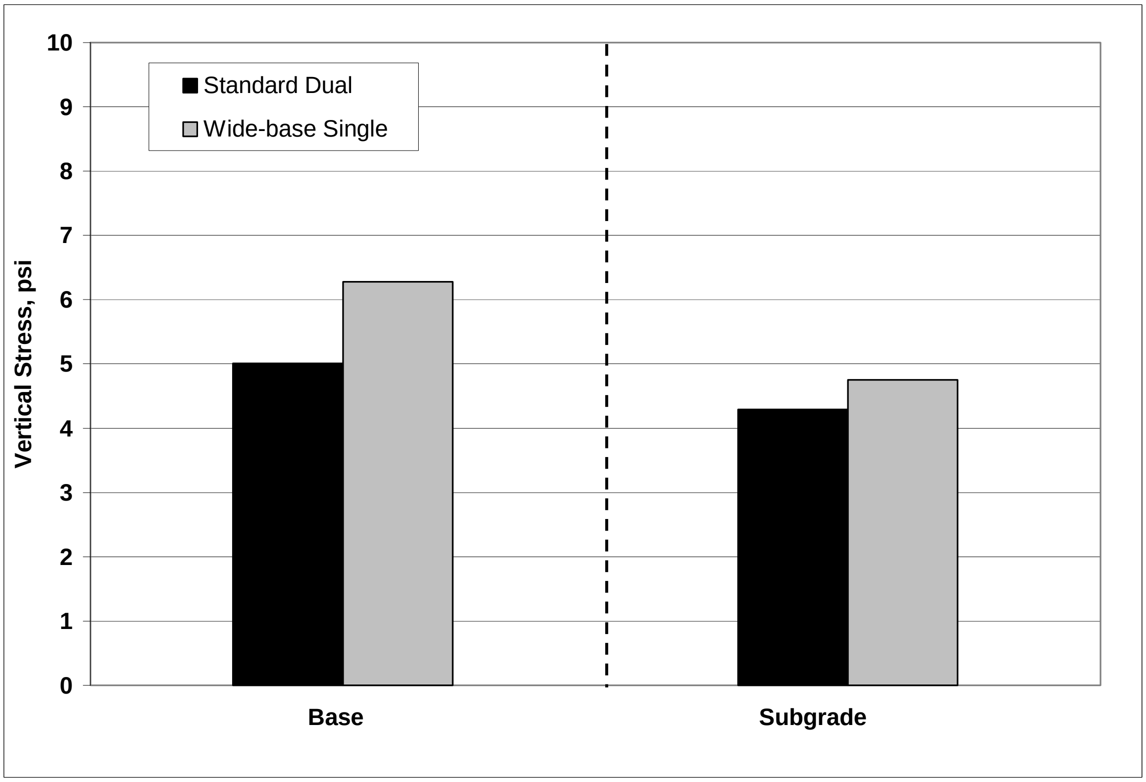

Figure 8. Calculated Vertical Stress on Top of the Base and Subgrade Layer.

The figures also illustrate another trend. Notice that with depth in the structure, the less distinguishable the two tire configurations become. As the load is transferred deeper and distributed over a greater area, the two configurations produce a similar response. For example, the strain measurements 7 in. deep in the structure (Figure 7) are quite different, and the effect of the wide-base single is evident. Yet, the difference is less apparent when considering the subgrade stress (Figure 8) which is an additional 6 in. deeper in the pavement structure. This trend can also be extrapolated to the surface of the pavement, where it is expected that the contact stresses are much higher under the wide-base single.

To understand the full implications of the wide-base tire, it is important to translate measured response to predicted performance or pavement life. In other words, what is the effect of a 46 percent increase in horizontal strain on the design life of the pavement? Translating mechanical response to pavement performance is the basis of mechanistic-empirical (M-E) pavement design. Equations, called transfer functions or performance equations, have been developed to empirically relate the number of cycles to failure, N_f, for a given measured or calculated pavement response. Many different transfer functions have been developed for both fatigue cracking and rutting, yet most fatigue models have the generic form of (Monismith, 1992):

$$N_f = k_1 \left[\frac{1}{\varepsilon} \right]^{k_2} \qquad (1)$$

where N_f = Number of cycles to failure
k_1, k_2= Empirical constants
ε = Measured pavement response

Research conducted at the Minnesota Road Research Project (Mn/ROAD) defined k_1 as 2.831e-6 and k_2 as 3.148 for fatigue cracking using the horizontal tensile strain at the bottom of the asphalt layer as the corresponding measured response, ε (Timm and Newcomb, 2003).

Using the calculated strain from WESLEA and the transfer function developed at Mn/ROAD, the predicted cycles to failure was determined for each of the given loading conditions, and the results are presented in Table 1. It is evident that the single tire configuration has magnified effects on the calculated design life. Theory predicts that the fatigue life under the wide-base single is 69 percent less than the conventional dual configuration under the same axle (18-kip) load. Considering only the theoretical information presented, it can be concluded that the use of this wide-base single will lead to premature failure and accelerated fatigue cracking development for the pavement section considered.

Table 1. Calculated Cycles to Fatigue Cracking Failure.

	Test Section N5	
Configuration	**ε_t, microstrain**	**N_f, cycles**
Standard Dual	151	3,028,815
Wide-base	220	929,002

FIELD TESTING

The second major component of this study was the field testing conducted in October, 2004 at the NCAT Test Track. Over two testing dates, the dynamic pavement response under the two loading conditions (standard dual tire and wide-base single) was measured via asphalt strain gauges and earth pressure cells. The data were then examined to investigate the effects of the two loading conditions and the accuracy of the layered elastic analysis explained above. Details are given below regarding the NCAT Test Track facility, testing sections, instrumentation, methodology, and results.

Test Facility

The NCAT Test Track is a closed-loop 1.7 mile full-scale asphalt pavement experiment test site located in Opelika, Alabama (Figure 3). Current experiments include a structural pavement study consisting of eight 200 ft test sections instrumented with strain, pressure, moisture, and temperature gauges. The instrumentation array is shown in Figure 9, and the gauges critical to this study were the strain and pressure gauges. These gauges recorded dynamic pavement responses under traffic loading at 45 mph.

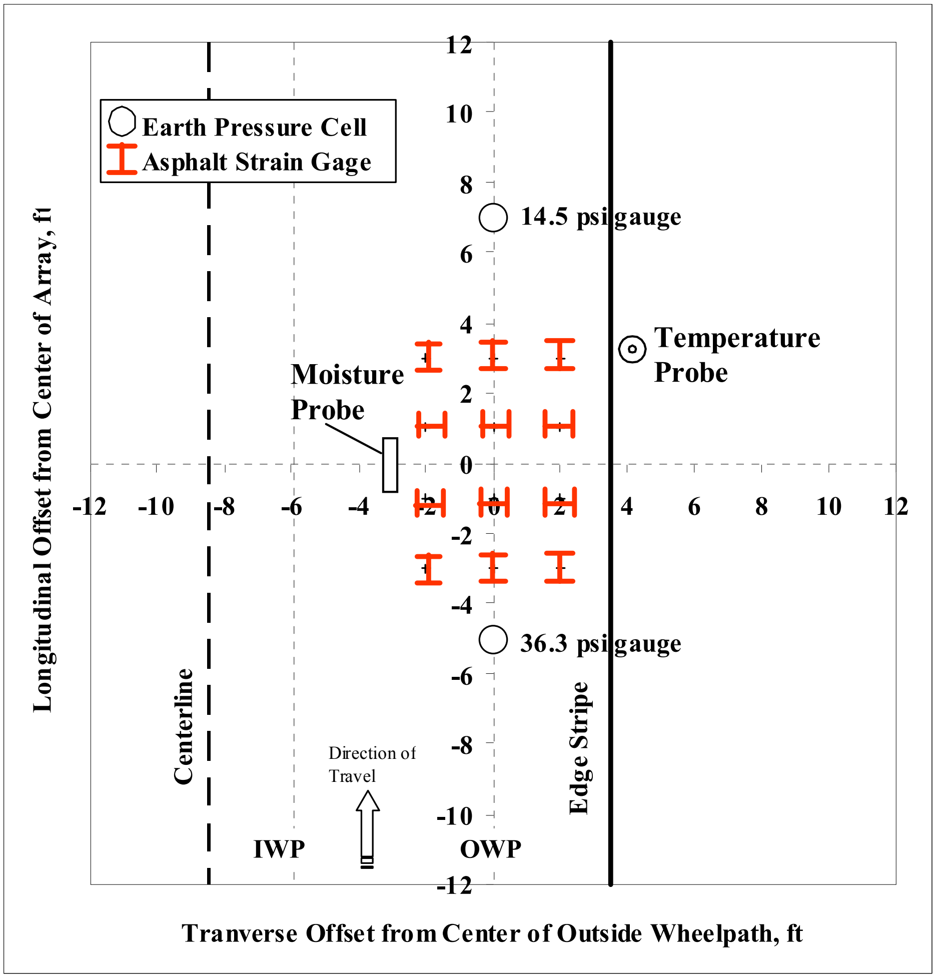

Figure 9. Instrumentation Schematic.

The eight test sections were designed at three different asphalt thicknesses, shown in Figure 10, using standard Alabama Department of Transportation (ALDOT) materials and mix design procedures. Two different asphalt binders were included in the structural study, a PG 67-22 and a polymer (SBS) modified PG 76-22, and the last two sections included a SMA surface layer. The PG 67-22 used in ALDOT mixes also meets PG 64-22 specifications. Test section N5 was used in this study because it represented the medium asphalt thickness (7 in.), and it had a relatively high number of operational gauges.

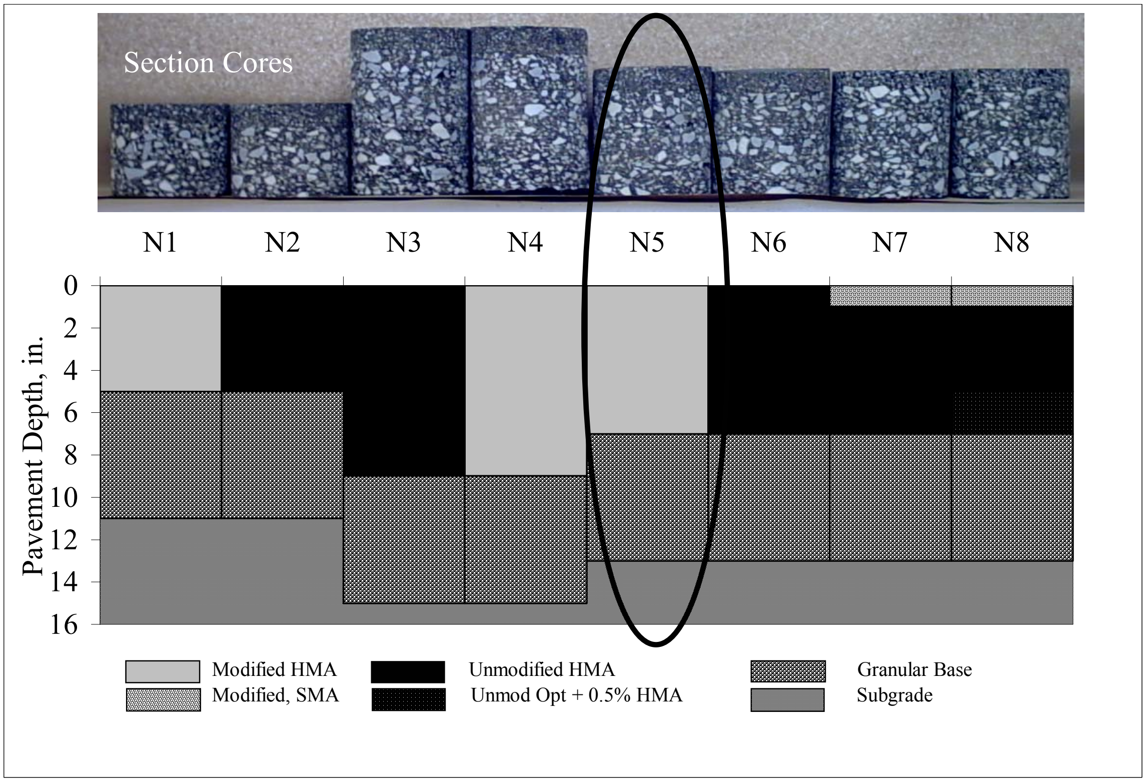

Figure 10. Structural Study Test Section Profile.

The NCAT Test Track is an ideal location for such a study as this because field pavement response can be measured accurately and analyzed quickly. In addition, the test sections are indicative of current Alabama pavements; therefore, the results are applicable to public access facilities. Other capabilities include long-term pavement performance monitoring that was not included in the objectives of this particular study.

Methodology

The goal of the field testing was to collect dynamic data from multiple truck passes of each loading configuration from test section N5 in order to compare pavement responses. Recall that the rear tandem axle group of the test vehicle was switched from eight dual tires to four single tires, shown in Figure 11.

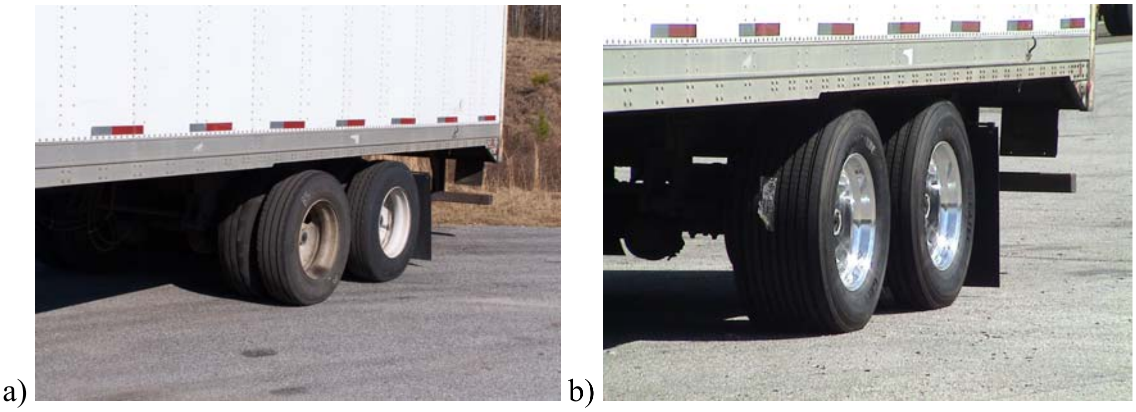

Figure 11. Rear Tandem Axel Group with a) Dual Tires and b) Wide-base.

In order to make comparisons between the two configurations, care was taken to ensure that the only experimental variable was the tire configuration. Therefore, the same test vehicle was used to guarantee identical axle load magnitude and distribution. Additionally, the same driver was used for both tests and was instructed on where to drive and maintained a testing speed of 45 mph for each pass. The third and most important variable was the testing temperature. Pavement response is highly dependant on the air and pavement temperature, especially in the asphalt layer because of the viscoelastic nature of the material. As a result, it was critical that the two tests were run at similar temperatures; otherwise, the strain and pressure readings would not be comparable.

Prior to testing, it was discovered that it took a few hours to switch the rear axle tires from single to dual, or vice versa. Due to the time delay, it was decided to conduct the testing over two days at a similar time-of-day where the temperatures would most closely match. The air and pavement temperatures were recorded during the first round of testing under the wide-base configuration, and then monitored the second day to determine the best time to test the dual configuration. This procedure worked well, and the temperatures matched nearly exactly. The average mid-depth asphalt temperature over the testing time for the first date was 72.0^{o}F, and the average mid-depth temperature for the second testing date was 72.4^{o}F. It is also important to note that the testing for this study did not interfere with any other research studies or delay the regularly scheduled trucking at the NCAT Test Track.

In addition to testing temperature, the measured pavement response is also sensitive to the load placement. That is, the location of the load in relation to the location of the sensor greatly affects the measured strain. Efforts were made to ensure that the truck traversed over the instrumentation location and a ‘direct hit’ was recorded. As mentioned, the same driver was used for both testing dates and was instructed on where to drive to maintain consistency and accuracy. The gauges are located in the outside wheel path of the lane (Figure 9) and were marked to help the driver align the vehicle as shown in Figure 12. Also, fifteen passes of the truck were recorded for each of the testing schemes to help guarantee that one of the recorded passes would be a direct hit. As will be shown later, fifteen passes was an adequate sample size for the analysis and accounted for testing variability.

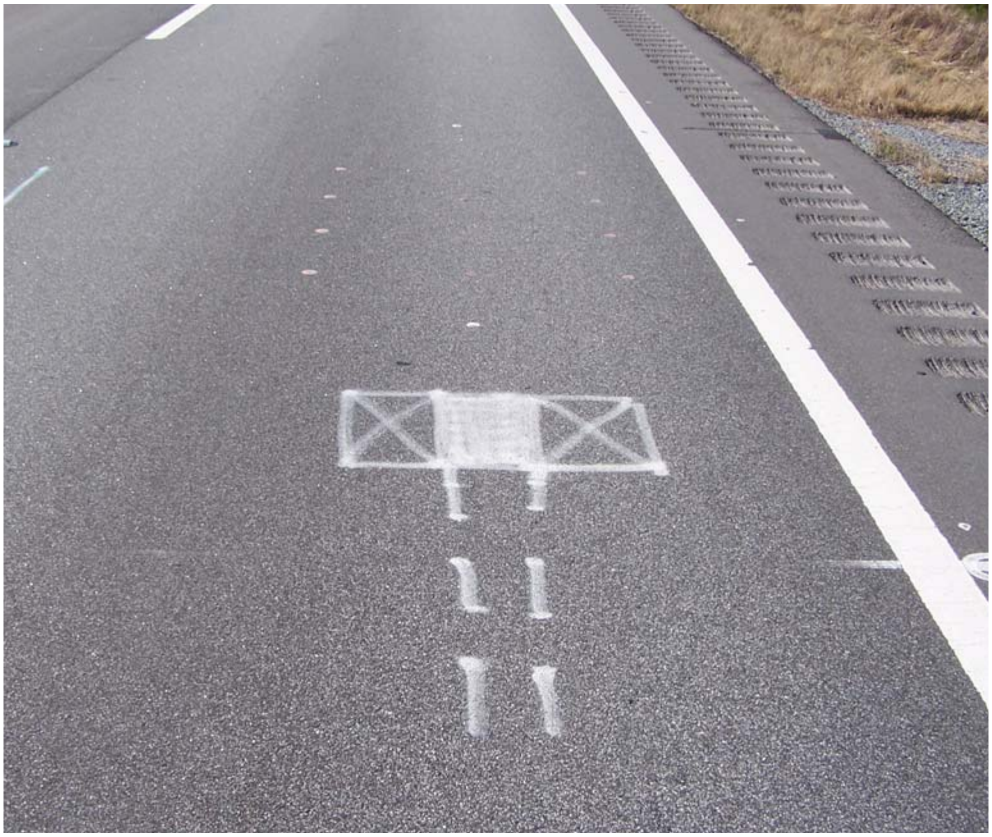

Figure 12. Pavement Markings to Guide Driver.

Data Collection and Processing

There are two main categories of gauges at the NCAT Test Track, dynamic gauges to measure response (stress and strain) and environmental instruments to measure in situ conditions (temperature and moisture). The environmental gauges are sampled at a low frequency of once per minute, and hourly averages are stored in a data logger housed in the road side box located at each test section. The data are then transmitted wirelessly and stored in the main Test Track research building. The dynamic gauges are sampled at a much higher frequency, 2,000 samples per second, to capture dynamic strain and pressure responses under a moving load. These gauges are sampled using a portable data acquisition system that connects to the road side box at each test section. The road side box, including the low frequency data logger and high frequency data acquisition system, is shown in Figure 13. This collecting scheme is powerful, relatively affordable, and convenient. More details on instrumentation, data collection, and data processing can be found in the following two NCAT reports: Design and Instrumentation of the Structural Pavement Experiment at the NCAT Test Track (Timm et al., 2004) and Dynamic Pavement Response Data Collection and Processing at the NCAT Test Track (Timm and Priest, 2004).

This study focused on the pavement performance data gathered from the dynamic or high speed gauges. An example of the recorded response of the test vehicle for both a strain and pressure gauge is given in Figure 14. From the figure, each axle is identifiable and the strain gauge shows

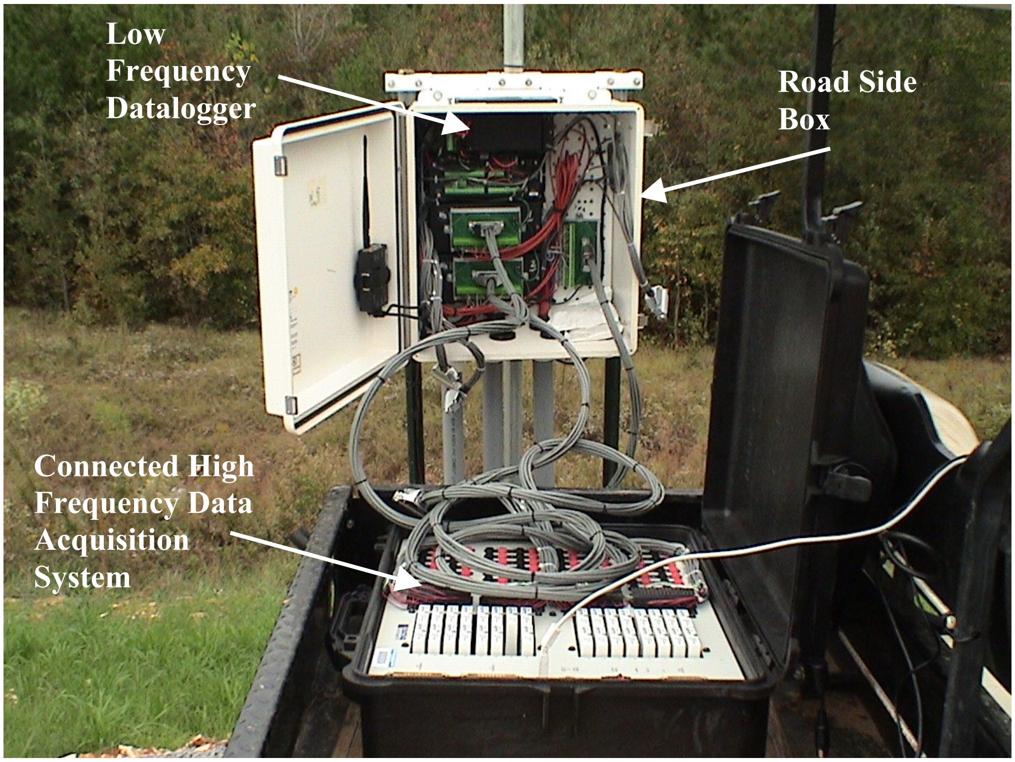

Figure 13. Data Acquisition System.

the smaller compression wave that precedes the tension spike as the tire approaches. All fifteen passes of each testing scheme were processed by axle group (steer, front tandem axle group, and rear tandem axle group) to obtain a corresponding strain or pressure reading. The rear axle was of greatest interest because it was the testing axle, while the steer axle was used as the control in the experiment.

Results and Discussion

Control Validation

To validate the testing procedure, it was important to first determine if the two testing conditions were in fact comparable. This was especially important because the testing was conducted on two different days. In other words, was the testing variability effectively minimized to produce replicate testing conditions? The recorded responses from the steer axle were used to evaluate the conditions of the two testing dates because the loading of the steer axle was not influenced by the tire configuration of the rear tandem axle or trailer, in general. Therefore, the steer axle response measurements should have been equal between the two collection dates. To consider variability in the collected data, a statistical analysis was performed to determine if the two samples (two test dates with different rear tandem axle configurations) of the steer axle response were statistically different. A t-test was performed with the null hypothesis that the two sample means were equal on the three measured responses, respectively. From the analysis in Table 2, it was found that the two sample means were not statistically different with 95 percent confidence. Thus, the testing conditions were considered equal. Also, the low coefficients of variation presented in Table 2 are evidence that the sample size of fifteen passes was sufficient, and the collected data were fairly precise and repeatable.

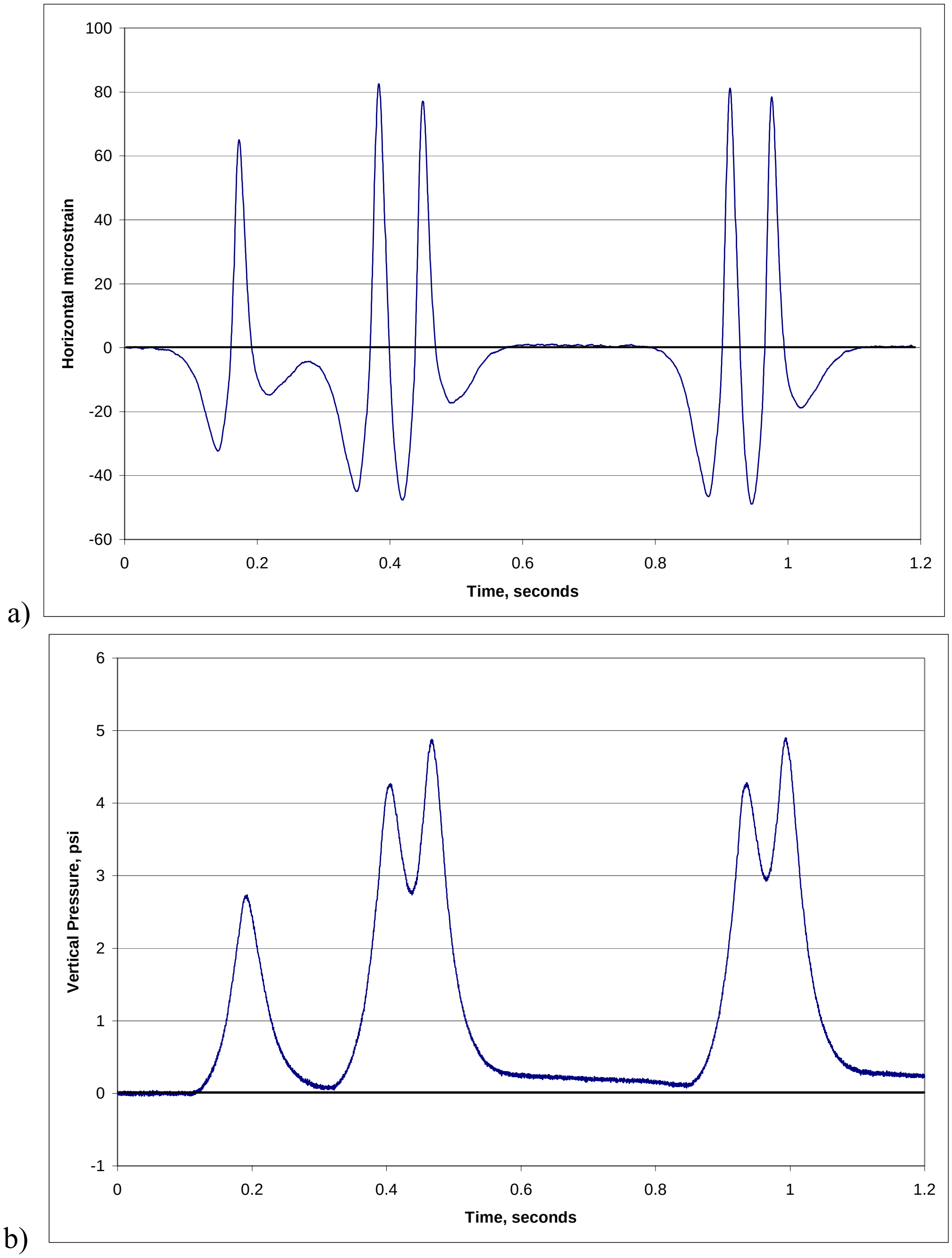

Figure 14. Dynamic Pavement Response a) Strain b) Pressure.

Table 2. Statistical Analysis on Steer Axle Response.

	Asphalt Strain (microstrain)	Base Stress (psi)	Subgrade Stress (psi)
Steer Axle Mean (with Standard Dual Rear Axle)	79.04	2.80	2.79
Coefficient of Variation, %	17.63	7.26	6.39
Steer Axle Mean (with Wide-base Single Rear Axle)	71.15	2.73	2.76
Coefficient of Variation, %	18.80	18.34	11.19
Sample Size	15	15	15
α	0.05	0.05	0.05
t Critical, 2 Tail	2.048	2.048	2.048
t-stat	1.583	0.541	0.332

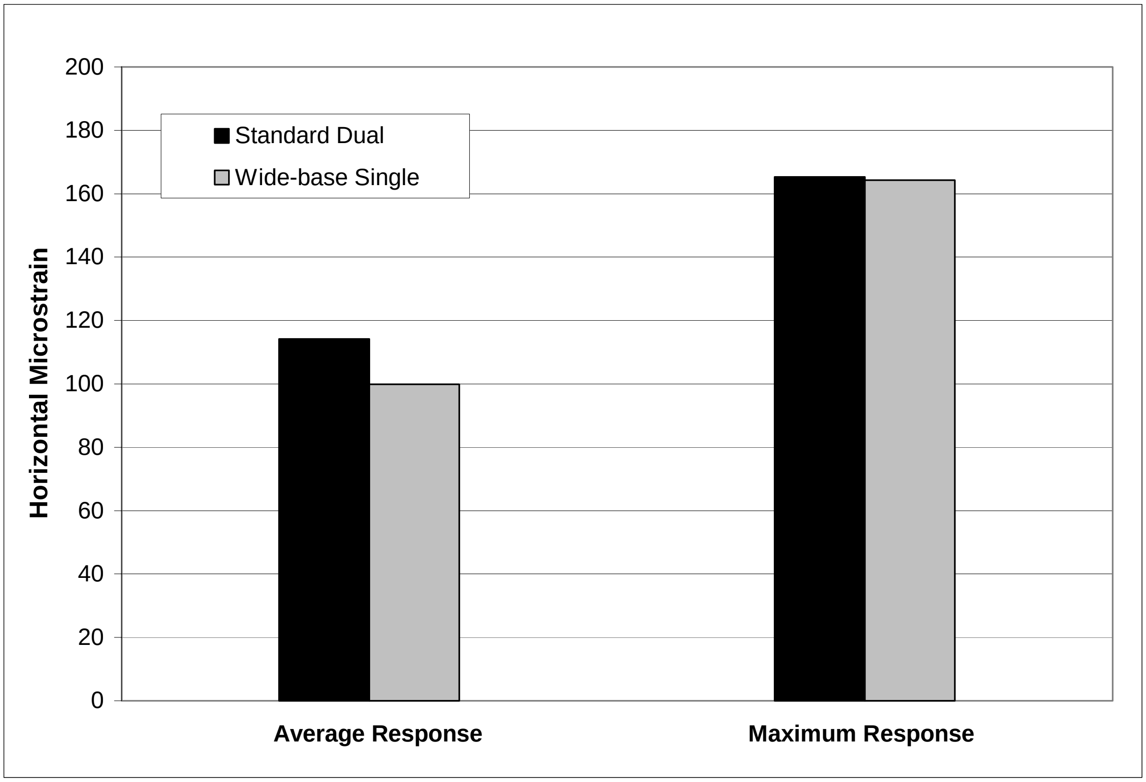

Figure 15. Field Measured Strain Response.

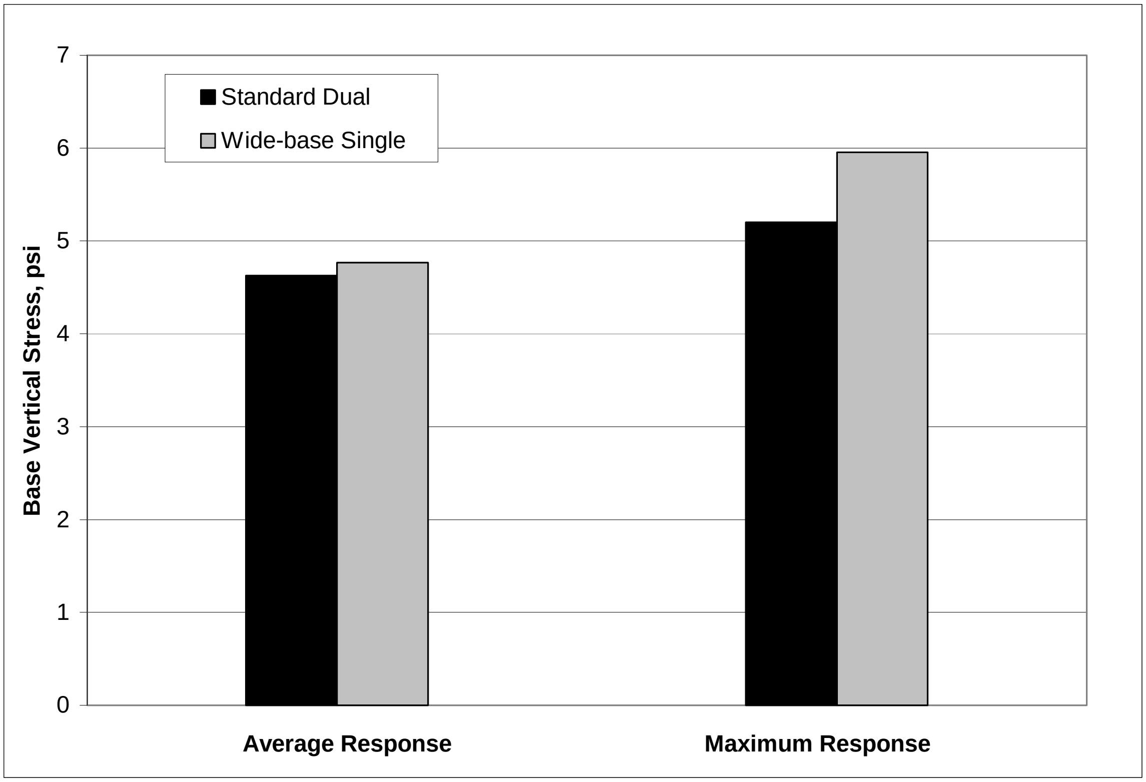

Figure 16. Field Measured Base Stress.

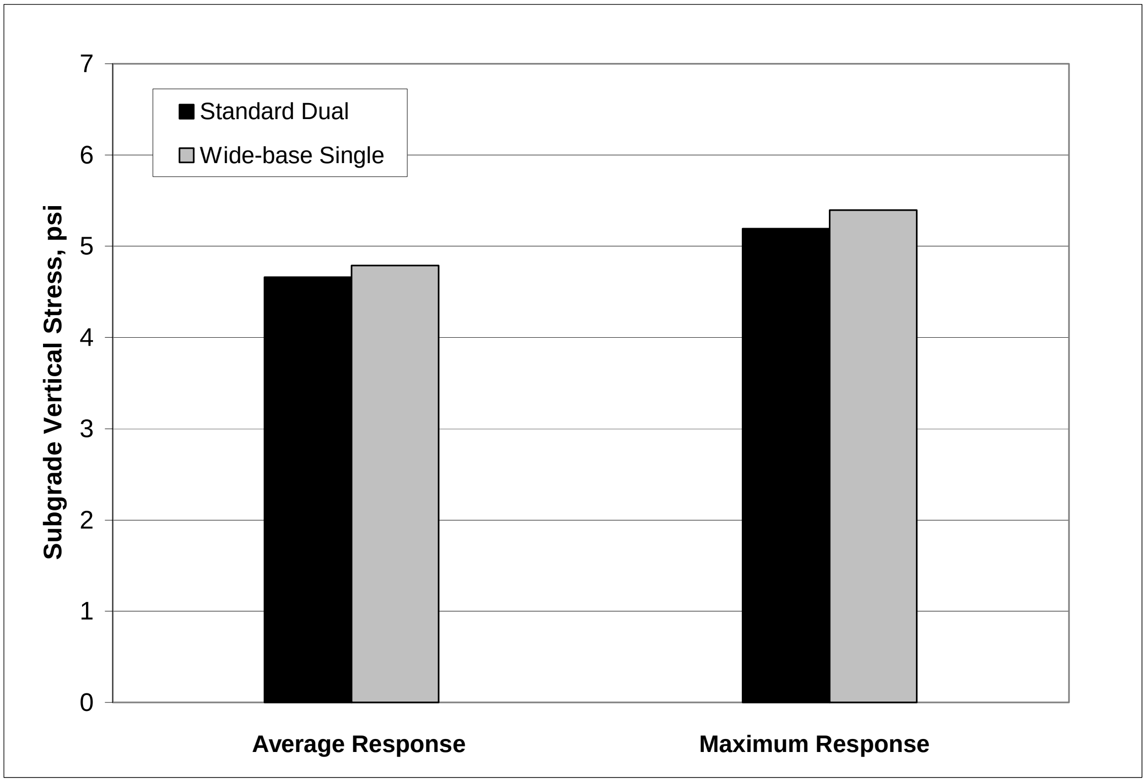

Figure 17. Field Measured Subgrade Stress.

Field Results

Once confidence was established in the testing scheme, the responses under the two tire configurations were compared. The results of the data processing are shown in Figures 15 through 17. Figure 15 reports both the average and maximum strain response from the fifteen truck passes. To further explain the figure, recall that the strain measurements are sensitive to lateral placement of the load; therefore, the gauge that best captures the true response is the gauge closest to the applied load. This is the reasoning for installing multiple strain gauges at different lateral positions, to ensure that one of the gauges is very near the load. In this study, the maximum recorded value among the strain gauge array was determined for each of the fifteen truck passes. Then the average and maximum value of the fifteen passes was calculated and is reported in Figure 15. The maximum recorded value is considered the response corresponding to a best-hit of the load on the gauge. The stress data are given in Figures 16 and 17 for the base and subgrade pressure plate, respectively. Because there is only one pressure plate per location, the stress data reported are simply the average and maximum of the fifteen recorded stress measurements.

It is evident from the figures that there was little to no difference in the measured pavement responses under both the standard dual and wide-base single tire configurations. The measured horizontal strain response at the bottom of the asphalt layer was nearly equal for both load configurations, as reported in Figure 15. The maximum recorded response differed by only 1 microstrain among the two. From Figures 16 and 17, the measured base and subgrade stress increased under the wide-base single by only 2.8 percent for both. A similar statistical analysis was done to compare the rear tandem axles as was previously done to compare the steer axles. Again, a t-test was performed assuming that the two sample means were equal at a 95 percent confidence level. From the results presented in Table 3, the two tire configurations caused statistically equivalent pavement response for the three considered measurements.

Table 3. Statistical Analysis on Rear Axle Group Response.

	Asphalt Strain (microstrain)	**Base Stress (psi)**	**Subgrade Stress (psi)**
Rear Axle Group Mean (with Standard Dual Rear Axle)	114.15	4.63	4.66
Coefficient of Variation, %	18.83	14.12	6.71
Rear Axle Group Mean (with Wide-base Single Rear Axle)	99.91	4.77	4.79
Coefficient of Variation, %	27.40	24.97	12.76
Sample Size	15	15	15
A	0.05	0.05	0.05
t Critical, 2 Tail	2.048	2.048	2.048
t-stat	1.585	0.332	0.732

The statistical information presented in Tables 2 and 3 gives additional information beyond the t-test. Notice that for all the measurements, the wide-base single sample is much more variable than the standard dual configuration. This may be an indication that the pavement response is more sensitive to the lateral placement with the wide-base single. It may also be simply part of the testing variability that was induced with field testing. Even with the noted restraints placed on this experiment, it was not possible to completely control the placement of a rear axle load of a semi-trailer traveling at 45 mph. For that reason, as noted above, multiple passes of dynamic field data were collected with multiple gauges, and the maximum reading was reported as the 'best-hit' or most accurate response.

In addition to the above comparisons of response magnitude, the dynamic traces themselves were investigated. Strain traces from both tire configurations are shown in Figure 18. The general behavior of both traces is nearly identical. This is further evidence that there is little to no detected difference between the two tire configurations in regards to the induced strain at the bottom of the asphalt layer.

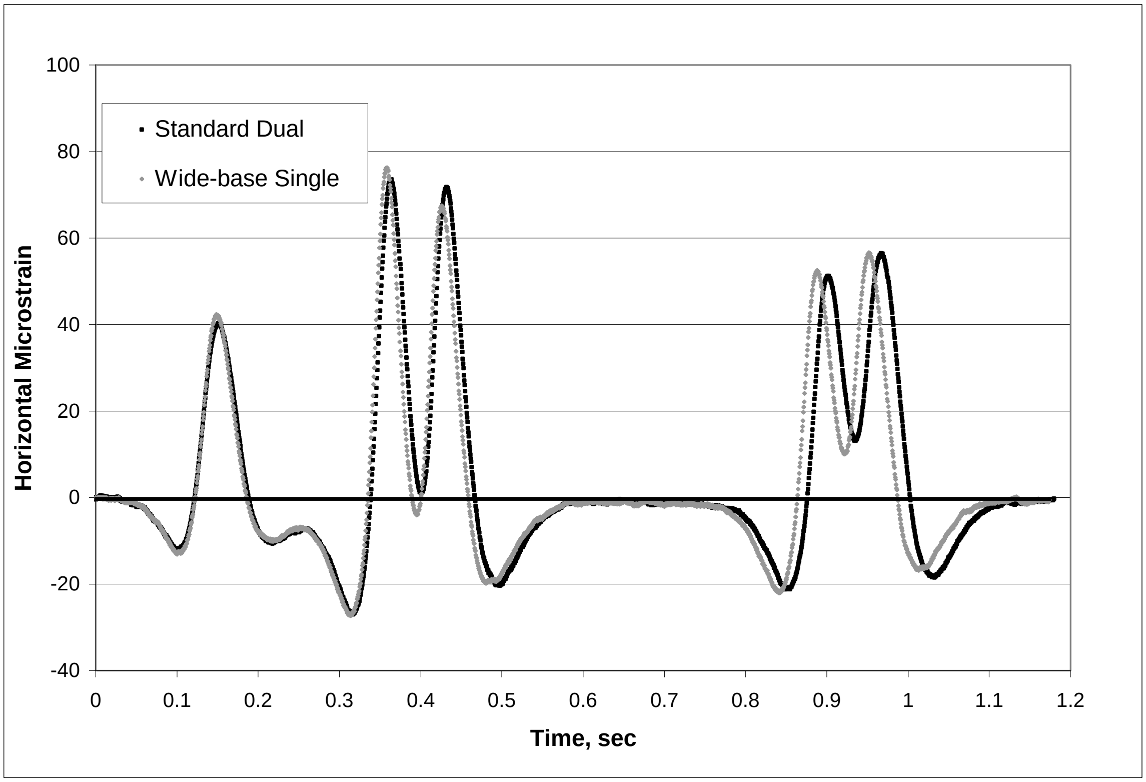

Figure 18. Dynamic Strain Trace.

From the colleted data presented in Figures 15-18, it can be concluded that the wide-base single tire (445/50R22.5) caused similar, if not identical, pavement response as the conventional dual tire assembly. In fact, the two configurations for the three measured responses (asphalt strain, base stress, subgrade stress) produced, statistically, the same results. Field testing of the same tire under similar testing conditions at Virginia Smart Road produced similar results (Al-Qadi et al., 2005). On relatively warm days, the strain responses between the two tire configurations were equal, although a slight increase in response under the wide-base was measured at their highest testing speed of 45 mph.

Measured vs. Theoretical Results

The third distinct objective of this study dealt with comparing the theoretical analysis and the field testing data. Figures 19 and 20 combine the predicted and measured values of the three pavement responses for the standard dual and wide-base single, respectively. It should be noted that the measured responses reported here are the maximum recorded responses, as discussed previously.

From Figure 19, linear layered elastic theory was reasonably accurate in predicting the pavement response. It under predicted the asphalt horizontal strain, base pressure, and subgrade pressure by 10, 4, and 21 percent, respectively. Again, to fully quantify the difference in the strain measurements, the theoretical and measured strains were used in a transfer function (Equation 1) to determine the effect on predicted pavement life. From Equation 1, WESLEA over predicted the cycles to failure by 36 percent. Although the discrepancy may be acceptable, it may cause concern because it is more preferable that the model tend to the conservative side rather than over predict pavement life.

The subgrade stress is the least accurate when compared to the field measured response, a difference of 21 percent. This inconsistency may be due to how the pavement cross section was modeled in the layered elastic model. Recall from Figure 4 that the granular base and improved subgrade were grouped together as a composite layer to determine the backcalulation modulus. Therefore, there may be some discrepancies between how the model predicts the load distribution within one layer and what is actually happening in the pavement structure between two layers.

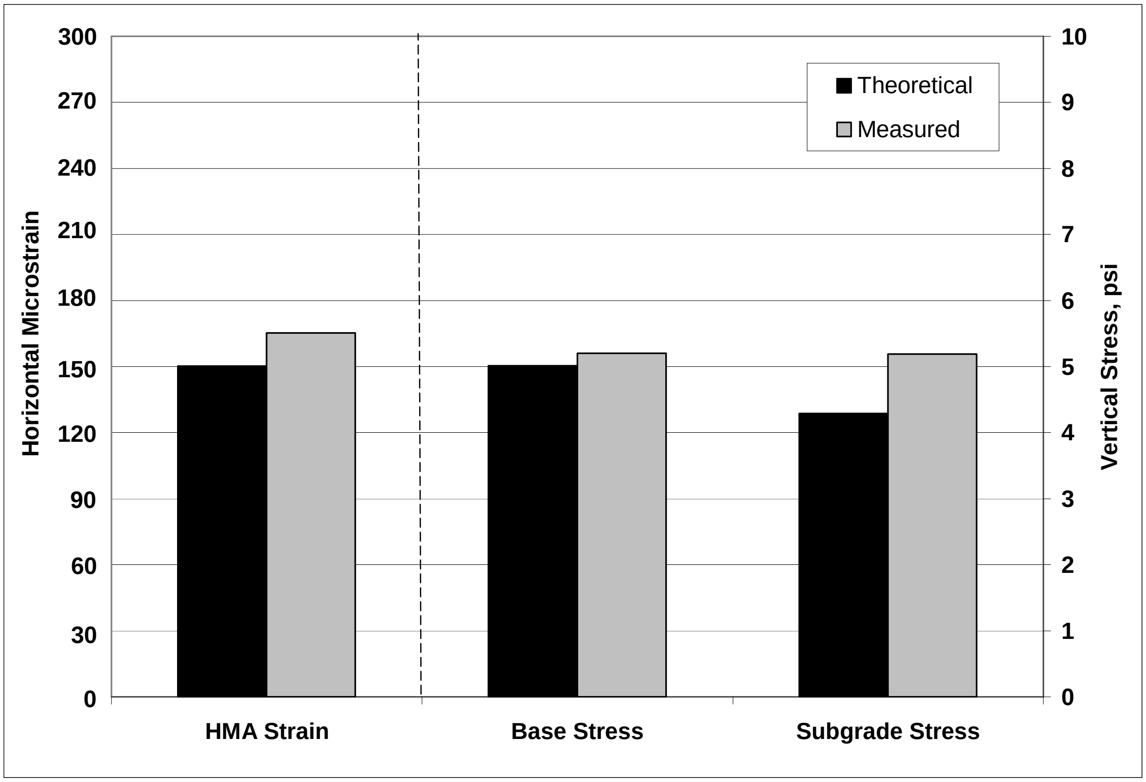

Figure 19. Theoretical vs. Measured Response for Standard Dual Configuration.

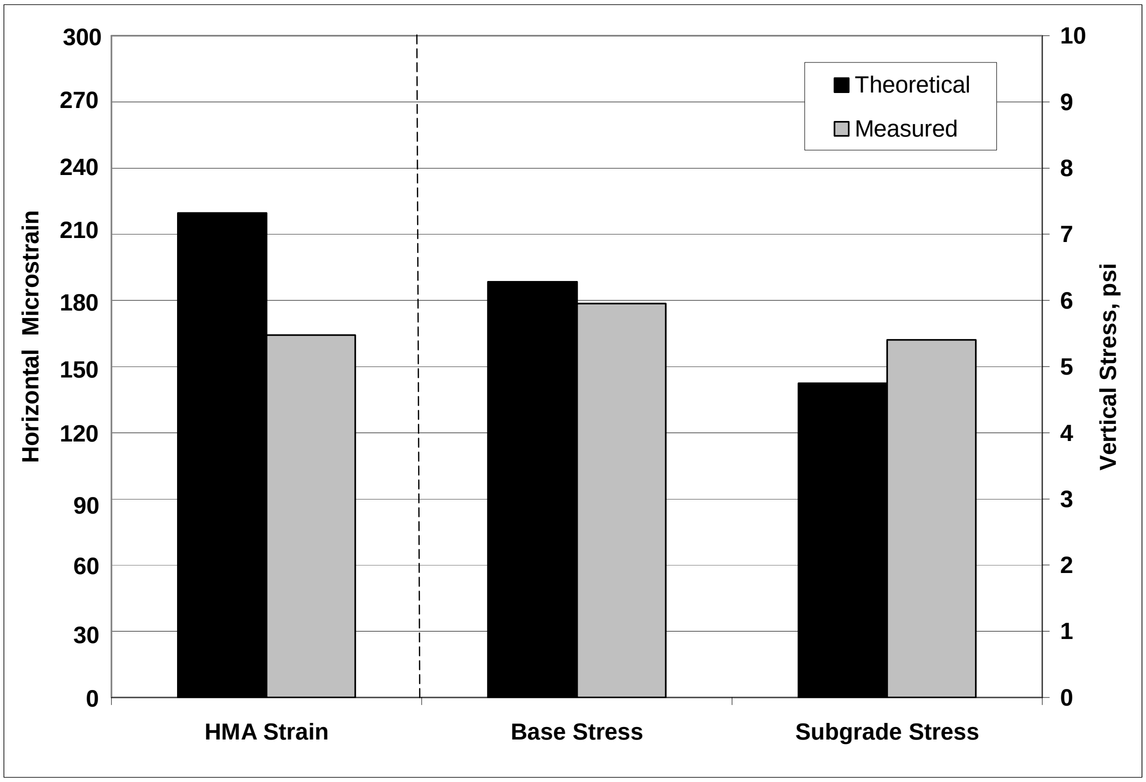

Figure 20. Theoretical vs. Measured Response for Wide-base Single Configuration.

The above discussion can be related to both the standard dual and wide-base single differences between the field measured and theoretically predicted stress responses. Yet, it is also important to note that the disagreement between field measured strain and predicted strain was more significant for the wide-base single tire configuration than the standard dual. WESLEA over predicted the strain response by 25 percent, over double the error for the standard dual configuration. As explored prior, the over predictions will have magnified effects on the calculated cycles to failure for fatigue damage. According to the strain values reported from WESLEA, the wide-base single configuration was predicted to decrease the pavement life by 70 percent; however, considering the field measured strain values, there is little to no predicted decrease of life (2 percent).

One of the major causes for the decreased accuracy of linear layered elastic analysis is due to the way the tire-pavement contact is modeled. In WESLEA, the load contact area is a circle with uniform pressure calculated from the tire load and inflation pressure. Prior research has shown that this assumption can be inaccurate, especially for wide-base tires. Siddharthan et al. (1998) reported that the loaded area of a wide-base single tire is noncircular, has a non-uniform contact stress distribution, and the applied vertical stress is greater than the inflation pressure. As a result, researchers have gone to great lengths to characterize and model the complexities of individual tire imprints and pressure distributions using sophisticated models like finite-element analysis (Al-Qadi et al., 2005). Yet, the use of linear layered elastic analysis given a tire load and inflation pressure is the state-of-practice for flexible pavement design and evaluation. In other words, even though it is possible to model the load more precisely, state agencies and pavement engineers will continue to use programs like WESLEA to determine damage criteria and pavement designs. For example, the forthcoming Design Guide developed under NCHRP 1-37A (2004) uses linear layered elastic theory given a tire load and pressure to evaluate pavement structural design.

Further investigation at the NCAT Test Track and by others should include a physical measurement of the contact area of the wide-base single tire (and dual tire) under loading. The area and dimensions could then be compared to what is calculated using the load-inflation pressure relationship. This measurement would be fairly simple and could be used to manipulate the layered elastic computer models to produce a result more consistent with the field measured response. Whatever the manner, if wide-base tires are to be introduced as a common tire configuration in the U.S., some care must be taken when including them in the design and evaluation of flexible pavements.

CONCLUSIONS AND RECOMMENDATIONS

Continuing investigation into the effect of loading parameters like tire size and configuration on pavement performance is important and necessary to both transportation agencies and the trucking industry. Based on the findings of this study, the following conclusions and recommendations can be made.

Conclusions

Regarding the layered-elastic theory analysis and comparison to field collected data, the following conclusions can be drawn:

1. The predicted responses using linear layered elastic theory for the standard dual tire assembly agreed reasonably well with the field measured responses with some discrepancy in the subgrade stress measurement attributed to how the pavement structure was modeled.
2. The theoretical model overestimated the horizontal tensile strain in the asphalt layer when compared to the field collected data for the wide-base single tire. The discrepancy between the predicted and field measured data was most likely due to the inaccurate assumption that the tire load is distributed evenly in a circular footprint calculated from the tire load and inflation pressure.

Further, the following conclusions can be made regarding the field measured methodology and pavement responses of the standard dual and wide-base single tire:

1. The testing scheme of collecting fifteen passes of each tire configuration over two testing dates at equal pavement temperatures was both efficient and effective in producing two equal testing conditions.
2. The field measured horizontal strain at the bottom of the asphalt layer was indistinguishable between the standard dual and wide-base single tire configurations. The similar response indicates that the predicted fatigue life is equivalent for the two tested tire configurations for the given testing conditions and pavement cross section.

3. The field measured base and subgrade stresses were statistically equal between the standard dual and wide-base single tire configurations, again indicating that the predicted rutting performance among the two configurations would be equal for the given test conditions.

Suggested Further Research

1. Further investigation should include measuring the tire footprint under load for both tire assemblies to compare between the actual and calculated load area used in the theoretical model.
2. Additional wide-base singles of varying sizes and inflation pressures should be evaluated in a similar manner as this study with varying pavement cross sections.
3. Further research should be conducted to investigate the effect of wide-base single tires on other pavement responses like surface shear stress that could lead to top-down cracking or surface rutting.
4. Field performance testing should be conducted to investigate the long-term effects of wide-base singles on pavement performance. In addition, current transfer functions should be evaluated for their accuracy in predicting pavement performance under wide-base single tire loading.

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