WIDE BASE SINGLE TIRES VS. DUAL TIRES: ASSESSMENT OF IMPACT ON ASPHALT PAVEMENTS

Joseph Ponniah, Ph.D., P.Eng.
University of Waterloo, Waterloo, Ontario

Ralph Haas Ph.D., P.Eng.
University of Waterloo, Waterloo, Ontario

Zhiyong Jiang, M.A.Sc.
University of Waterloo, Waterloo, Ontario

Ron Madill
Ontario Ministry of Transportation, London, Ontario

Adedamola Adedapo
University of Waterloo, Waterloo, Ontario

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ABSTRACT

The Ontario Ministry of Transportation initiated a research project in 2006 with the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo to assess the potential impact on pavements and the associated cost if the axle load on the second generation single wide-based tires (SWB) was increased to 9000 kg. The scope of this study included a comprehensive experimental investigation using the instrumented pavement sections. The objectives of the experiment were: 1) to determine the axle load on dual tires that would be equivalent to a 9,000 kg single axle load on the SWB tires and 2) to examine the effects of unequal tire pressure, wander and tire types on pavement response.

The results showed that the axle load on dual tires causing the equivalent damage as the 9000 kg axle load on SWB tires could range from 10,700 kg to 12,300 kg depending on the pavement structural strength. The weaker the pavement, the greater the damage due to SWB tires. The analysis based on ESAL indicated that the SWB tire could potentially cause 2 to 3.5 times the overall damage caused by dual tires. The fatigue cracking analysis showed that the SWB tires could cause 1.7 to 1.9 times the damage associated with dual tires. The study indicated that the combined adverse effects of unequal tire pressure on dual tires, wander, dynamic load and speed do not give SWB tires any advantage over dual tires in terms of reducing the overall pavement damage.

INTRODUCTION

Super single tires have been used for many years; their usage has been limited because they were heavy and much larger in diameter than dual tires and cause more damage to pavement at equivalent axle loads. Therefore, provincial governments have generally restricted the axle load on these tires.

Recently, tire manufacturers are producing a second generation new technology low-profile SWB tire with a diameter that is identical to dual tires. These manufacturers have approached the Province of Ontario and other provinces requesting that provincial regulations be modified to accommodate the use of the new generation SWB tires as a viable replacement for dual tires. Based on their own research, they found that the second generation SWB tires would cause no more infrastructure damage than dual tires while improving fuel efficiency between 6% and 10%, compared with standard dual configurations. It is likely that the second generation SWB tires will replace many of the existing conventional single tires as well as become attractive alternatives to dual tires. This tendency could lead to a modification of the national standard if the provinces achieve consensus.

The position of highway agencies, including Ontario Ministry of Transportation (MTO), is that research related to the impact of SWB tires on pavement at axle loads above 8,000 kg has been contradictory and inconclusive [1]. Thus, further testing was carried out at the Centre for Pavement and Transportation Technology (CPATT) test section at the University of Waterloo to address the concerns among highway agencies on the impact that SWB tires at axle loads up to 9,000 kg could have on pavements.

SCOPE AND OBJECTIVES

The scope of this study focused on the experimental investigation of the effect of the second generation SWB tire (455/55R22.5) on pavements in comparison to the dual tires using the instrumented CPATT field testing facility at the University of Waterloo. In addition, a literature review of work done by other agencies [2,3,4,5,6] was conducted.

The objectives of this study were: 1) to assess the potential pavement damage if the axle load on second generation SWB tires were increased to 9,000 kg based on direct field measurements of the pavement response under normal and dynamic loadings; and 2) to examine the effects of unequal tire pressure, wander and tire types on pavement response

CPATT TESTING FACILITY

The CPATT test track is located near the University of Waterloo campus. It is a 700 m long and 8 m wide two-lane road with an instrumented test section consisting of 200 mm asphalt layers (100 mm HL-3 surface course and 100 mm HL-4 binder course). The thickness of granular A base is 300 mm and granular B sub-base 300 mm. Figures 1 and 2 show the locations of sensors installed in pavement layers [7].

EXPERIMENTAL PROGRAM

The field testing was carried out in two phases involving direct measurements of tensile strains at the bottom of the asphalt pavement layer under different axle loads on both dual and SWB tires. Phase 1 was conducted in June 2006 and Phase 2 was conducted in October 2006. Specifically, the field measurements were taken to determine the single axle load on dual tires that would cause the same pavement response as the SWB tires at a single axle load of 9,000 kg. The experimental program is described as follows.

Phase 1

With support from the trucking and tire industry, suitable trucks equipped with both dual and SWB tires were used to compare the pavement response under different loading. The truck was equipped with a moveable load on the deck and a liftable dual axle. The rear wheels of the dual axles was fitted with SWB tires and the other front wheel was fitted with dual tires (Figure 3). The loads on the deck were moved back and forth as needed to achieve the desired axle load required for each test. The exact location and the acceptable offsets of the sensors were identified as shown in Figure 4. The pavement response was assessed in terms of measured tensile strains under the asphalt pavement. The Phase 1 field testing consisted of eight main tasks:

Tasks 1- 2:	To determine the equivalent single axle load on dual tires causing the same pavement response as SWB tires when loaded at 8,000 kg and 9,000 kg.
Tasks 3- 7:	To quantify the potential adverse effects of 1) dual tires due to unbalanced loads, 2) lateral wander, 3) speed, 4) different dual tire types, and 5) dynamic loadings.
Tasks 8:	To compare the stress under both tires based on contact area measurements.

Task 1 was designed to estimate the axle load on SWB tires equivalent to the allowable single axle load of 10,000 kg on dual tires in Ontario. In this case, the load on the SWB tires was increased from 7,000 kg in increments of 1,000 kg until the strain under the SWB tire was equal to the strain under dual tires at 10,000 kg. Task 2 was designed to estimate the load on dual tires equivalent to the axle load of 9,000 kg on SWB tires. This load is referred to as equivalent axle load on dual tires (EALDT) in subsequent discussions. In this case, the load on dual tires was increased from 8,000 kg in increments of 1,000 kg until the strain under the dual tires was equal to the strain under the 455 mm SWB tires at 9,000 kg. EALDT was used to estimate the potential increase in pavement damage if the axle load restriction on SWB tires is increased to 9,000 kg.

Each test was repeated a minimum of five times until at least three acceptable test results were recorded on each lane. The test was considered acceptable if the tire passed within the offset limits (± 150 mm) of the sensor location. During the testing, the speed, offset measurements, and pavement surface and subsurface temperatures were recorded.

Additional tasks (Tasks 3-8) were carried out at the request of the stakeholders to investigate the reported specific adverse effects of dual tires on pavements in comparison to SWB tires.

In Phase 1, the SWB tires and dual tires had to be tested at different times because of the need to switch tires. To avoid potential variability in the strain measurements associated with temperature, the experiment was specifically designed so that the time interval between tests was short enough to make negligible the effects of temperature variation on strain measurements. Unfortunately, the delay between some tests in Tasks 1-2 was inevitable because of equipment breakdown and other unforeseen circumstances.

As a result, significant variability in the strain measurements was observed, particularly in Tasks 1-2, because of changes in pavement temperatures during the testing. This variability made it difficult to draw conclusions with a high confidence level. There was a need for an improved testing method under similar environmental conditions in terms of time and temperature to reliably determine the equivalent axle load on duals causing the same damage as SWB tires loaded to 9,000 kg. This concern was addressed in the Phase 2 experiment.

Phase 2

The Phase 2 involved the use of the two test trucks simultaneously, one equipped with SWB and the other with dual tires respectively, as shown in Figures 5 and 6. The test schedule was specifically designed to compare the impact of both tire types on the pavement at the same test time and temperature. This objective was achieved by driving one truck over the sensor, followed by the second truck within a two minute interval.

A total of five tests were conducted with each test consisting of four repeated trials in order to acquire four pairs of observations within the allowable offset tolerance limits from the sensor location. The load on SWB tires was maintained at 9,000 kg throughout the experiment while the load on dual tires was increased from 9,000 kg to 13,000 kg in increments of 1,000 kg. The order of trucks was alternated after each trial.

The analysis of the results from Phase 1 indicated the need for calibration of tensile strain measurements for different offsets (tire location away from the sensor) since it was difficult for trucks to consistently drive over the exact sensor location. As a result, the tensile strain measurements at different offsets were taken for the dual and SWB tires at a controlled speed of 8 kph (Figure 7). This was designed to ensure accurate measurements of offsets at a constant speed. It was assumed that the percent decrease in the observed strain associated with different offsets is the same at different test speeds.

FIELD TEST RESULTS AND DATA ANALYSIS

Phase 1 - Results

Task 1- 2: Preliminary Assessment of Equivalent Dual Axle Load (EALDT)

Preliminary test results indicated that SWB tires at 9,000 kg axle load could potentially cause more pavement damage than the best-performing dual tires at 10,000 kg axle load. However, as explained in the previous section, there was scatter in the results due to the effects of two parameters: a) temperature variation during testing, and b) the duration of pavement exposure to high temperature in between testing. In other words, the strain measured at the same surface temperatures on the same day but at different times would be different under the same axle load.

Therefore, the comparison between the two tires based on tensile strains (Task 1-2) observed at different times of the day would not be appropriate. This issue was resolved in Phase 2 testing.

However, the tests in Phase 1 under Tasks 3-8 were carried out as per schedule and there was no undue delay between the tests to cause any variation in the observed strain values within the data set. Hence these tests were not repeated in Phase 2.

Task 3: Effect of Unequal Tire Pressure

The purpose of Task 3 was to assess the effect of unequal dual tire pressures on pavements. The inflation pressure of the inner tire of the dual set was reduced as the inner tire pressure is not routinely checked due to the poor accessibility. The tests were carried out maintaining the outer tire pressure at 100 psi throughout while adjusting the inner tire pressure from 100 psi to 90 psi and finally 80 psi. The pavement subsurface temperature was an average of 25^{o}C.

The maximum strain values in Figure 8 correspond to a situation where one of the dual tires carrying the maximum load was closest to the sensor location. Therefore, the maximum strain value is expected to provide a realistic assessment of the maximum potential impact of imbalanced loading of dual tires. Figure 8 shows that the difference in the maximum strain values is less than 0.3%, which is insignificant. This result could be partially due to the fact that imbalanced loading on dual tires is caused not only by unequal tire pressures but also by other factors such as the centre-of-gravity of the payload and pavement surface irregularity. The average strain values indicated that the imbalanced loading on dual tires potentially increases the strain on pavement by 1.7% to 3% in comparison to the equal loading on dual tires.

Task 4: Effect of Wander

Figure 9 shows the effect of wander on tensile strains. The tensile strains were measured when trucks crossed over and away from the target (wander). In this case, the axle loads of 10,000 kg and 9,000 kg were used for dual tires and 455/55R22.5 SWB tires respectively.

The effect of wander is assessed in terms of the reduction in the strain level as the wheel wanders away from the wheel path. The higher the reduction, the better the effects of lateral wander. In this case, the percent reduction for dual tires and 455/55R22.5 SWB tires are 55% and 34% respectively (Figure 9). Contrary to the common belief, the results from this study indicated that dual tires are superior to SWB in terms of reducing the damage associated with wander.

Task 5: Effect of Speed

Figure 10 shows the effect of speed on tensile strain for dual, SWB tires 445/50R22.5 and 455/55R22.5. The data for 455/55R22.5 at low speed (<25kph) are not available. The test results show that tensile strain decreases as speed increases for both tires. However, dual tires produce about 10% higher strain than SWB tires at a speed of 8 kph and about 10% lower strain when the speed was 40 kph. The observed strains for both tires were equal at 15 kph. The subsurface temperature was about 25^{o}C, which corresponds to the surface temperature of 40^{o}C plus. It is indicated that at highway operating speeds the dual tires potentially perform better than the SWB tires in summer. However, more tests are needed to validate this observation particularly the higher strain for dual tires at creep speed.

Task 6: Effect of Different Types of Dual Tires

Task 6 included testing different tire types in order to address stakeholders' concerns that numerous dual tires are available in the market that might cause more damage than the typical 11R22.5 dual tires.

As shown in Figures 11a and 11b, the axle loads on different types of dual tires were similar with a variation less than 2%. The observed tensile strains for 275/80R22.5 and 295/75R22.5 type tires are comparable but they are less than the values obtained for 11R22.5 tires at 26°C. Figure 11b shows that the tensile strain for 11R22.5 dual tire is smaller than the values obtained for 285/70R19.5 type dual tires and 455S SWB tires. In all cases, SWB tires show higher strain than all types of dual tires. It appears that the effect of different types of dual tires is not significant on the overall assessment of pavement damage associated with SWB tires.

Task 7: Effect of Dynamic Loads on Dual and SWB Tires

The effect of dynamic loading with different types of tires is assessed as the trucks passed over a speed bump at 8 kph. The results are shown in Figure 12. However, the test results for 455 SWB tires are not accurate because the dual tires in front of the single tire axle could not be lifted high enough to drive over the speed bump. In this case, the test was conducted by reversing the truck at slow speed. The speed while reversing was difficult to control. The results show that the dual tire under dynamic loading produces less strain than SWB tires under normal and dynamic loading situations.

Dynamic loading is caused by road surface roughness when trucks operate at high speeds. Perhaps the strains observed at high speeds are also closely related to the dynamic effect in the field in addition to the speed bump test. In this case, the observed strains at high speeds for dual tires are less than the strains observed for the SWB tires (Figure 10). This supports the results observed from the speed bump test. In conclusion, the results show no evidence of additional benefits of using SWB tires under dynamic loading.

Task 8: Measurement of Contact Area/Contact Stress

Contact area measurements under each tire at different axle loads were taken just before each test. The average contact stress values were calculated by dividing the axle load by the contact area assuming a uniform stress distribution across the contact area. In reality, the stress distribution is not uniform across the tire width. However, the stress induced on pavement by a moving axle load is normally distributed across the wheel path due to wander effect. Therefore, the assessment based on average contact stress closely reflects the effect of normally distributed stress on pavement in the field. As shown in Table 1, the contact stress for 455 SWB tires under a 4,540 kg static load per wheel is 1500 kPa and is about 20% higher than the contact stress (1249 kPa) observed for dual tires under the same load.

Phase 2 - Results

The second phase of field testing was conducted for three days as follows:

- Day 1: Offset and speed tests
    - Tensile strain measurements at different tire contact positions and at different speeds with Duals @ 10,000 kg and SWB @ 9,000 kg

- Day 2: Primary tests 1- 5
    - Duals @ 9,000 kg, 10,000 kg, 10,500 kg, 11,000 kg, and 12,000 kg and SWB @ 9,000 kg

- Day 3: Additional tests 6-9
    - Duals @ 9,000 kg, 10,000 kg, 10,500 kg, 11,000 kg, and SWB @ 8,500 kg and 9,000 kg

Selection of Suitable Field Data for Analysis

Following consultation with stakeholders and clients, the analysis was carried out by pooling the data collected over three days. Concerns were raised by the stakeholders regarding the higher values and larger variability of tensile strains observed for the eastbound lane. To address this concern, statistical analyses were conducted to ensure that the pooled data was suitable for further analysis. The significance of the variation in the data was assessed in terms of mean, standard deviation and coefficient of variation (COV). A regression technique was used to examine the relationship between the tensile strain and the load on different tires for both westbound lane (WBL) and eastbound lane (EBL). This analysis was intended to: 1) assess whether or not the difference in the observed readings between the WBL and EBL was due to a potentially defective sensor installed in the EBL; and 2) determine the equivalent axle load on dual tires (EALDT) potentially causing the same damage as SWB tires loaded at 9000 kg if the data is valid. The results based on the statistical analyses indicate that the observed variation of tensile strains underneath the pavement in both WBL and EBL lanes under different axle loads for both tires are consistent and the data is considered suitable for further analysis.

Additional investigation using a falling weight deflectometer (FWD) was carried out to determine the reason for the difference between the WBL and EBL readings. The average FWD measurement for EBL is about 26% higher than the deflection obtained for WBL (Figure 13). This result confirms the preliminary assessment by pavement experts that the higher strain values associated with EBL was primarily due to the lower EBL pavement structural strength than WBL. The examination of construction historical data revealed that the EBL section was built on the fill area while WBL was on the existing ground line. This observation probably explains why the measured deflections were different for the two lanes.

Estimation of Equivalent Dual Axle Load on Dual Tires (EALDT)

Figure 14 shows the relationship between the axle load and the strain observed on WBL and EBL sections for both tire types. For the WBL section, the axle load on dual tires producing the same strain as SWB tire at 9000 kg is 10,700 kg which represents EALDT by definition. Similarly, the EALDT value for the EBL section is 12,300 kg corresponding to 9000 kg on the SWB tires. As discussed before, the reason for higher EALDT for EBL section in comparison to WBL is due to the differences in pavement structural strength. The weaker the pavement, the higher the EALDT value. This finding was supported by the Quebec study [2] which showed that EALDT could increase up to 17,000 kg when the pavement became weak during the spring season, while EALDT during the summer was 11,000 kg when the pavement was strong.

Assessment of Pavement Damage

An analysis was conducted to compare the pavement damage caused by the SWB and dual tires based on the EALDT calculated above. In this analysis, two approaches were used. In the first approach, the damage was assessed in terms of equivalent single axle load (ESAL). The concept of ESAL was originally developed by AASHTO for converting mixed mode traffic to an equivalent number of 80 kN single-axle loads for pavement design application. The higher the ESAL value, the greater the damage. In the second approach, the damage was assessed in terms of its potential failure due to fatigue cracking.

Equivalent Single Axle Load (ESAL) Approach

In this case, the damage between SWB tires and dual tires is compared based on ESAL ratio. ESAL was calculated using the following equation [8]:

$$\text{ESAL} = (0.01169L + 0.064)^{(4+8.9/L)} \qquad (1)$$

where, L = Axle load in kN

Table 2 presents the calculated ESAL for the SWB and dual tires. It indicates that the SWB tire can potentially increase the damage 2 to 3.5 times the damage caused by dual tires, depending on the pavement strength. The associated pavement damage cost is estimated by multiplying the increased ESAL value by the Cost/ESAL/km for different highways. The results were published in the report [12].

Fatigue Approach

This assessment was based on the ratio of fatigue damage associated with SWB tires and dual tires. Fatigue damage is caused by repeated axle load applications. It is a progressive localized damage due to repeated stresses and strains in the material [9]. To quantify the fatigue damage due to different tire types, a fatigue model suggested by Finn et al. [10] was used:

$$\text{Log } N_f = 15.947 - 3.291 \log(\varepsilon_t/10^{-6}) - 0.854 \log(E/10^3) \qquad (2)$$

where, N_f = Load repetitions to Failure
ε_t = Horizontal tensile strain at the bottom of asphalt concrete
E = Elastic modulus of the asphalt concrete, MPa

Table 3 presents the tensile strains measured at the bottom of the 200 mm HMA layers as well as the predicted number of repetitions before fatigue failure occurs for both tires. The result indicates that the SWB tire can potentially cause 1.7 to 1.9 times the damage caused by dual tires, depending on the pavement strength.

SUMMARY AND RECOMMENDATIONS

The findings of the experimental investigation carried out in Phase 1 and Phase 2 are summarized as follows.

Phase 1 Study

- Pavement temperature had an unexpected high impact on the test results. There was a strong correlation between the tensile strain readings and the sub-surface temperature.

- Additional, more focused field testing was therefore conducted to minimize or eliminate the impact of the temperature fluctuations and to provide additional data readings to help fine-tune the original calibration.

- Preliminary test results indicated that SWB tires at 9,000 kg axle load could potentially cause more pavement damage than the best-performing dual tires at 10,000 kg axle load.

- Imbalanced loading due to unequal pressure had no effect on maximum tensile strains. However, the average strain was slightly increased when the tire pressures were not equal. More tests are needed to determine the effects of such difference on pavement performance. According to the European study, unequal tire pressure has the potential to increase rutting by only 1% relative to SWB tires [11].

- The vehicle lateral wander appears to have no beneficial effect on SWB tires in terms of reducing the potential damage. On the contrary, the dual tires showed a significant reduction in the tensile strain due to wander in comparison to SWB tires.

- The dual tires produced lower strain than the SWB tire at 40 kph and higher strain at 5 kph when surface temperature was 40°C during the summer.

- Dynamic loading tests showed that the dual tire under dynamic loading produces less strain than SWB under normal and dynamic loadings.

- Contact stress test results indicated SWB tires produce 20% higher stress than the dual tires under the same axle loading.

Phase 2 Study

- The single axle load on dual tires equivalent to the SWB tires at 9,000 kg appears to vary with pavement strength. The weaker the pavement, the higher the equivalent axle load on dual tires (EALDT).

- The results identified two EALDT values (10,700 kg and 12,300 kg) for WBL and EBL sections, respectively. The average EALDT value is 11,500 kg.

- Based on the analysis of ESAls, the SWB tire could potentially cause 2 to 3.5 times the damage due to dual tires.
- Based on Fatigue analysis, the damage due to SWB tire could be 1.7 to 1.9 times the damage caused by dual tires.

Recommendation

Future work should focus on the experimental validation of the EALDT values for high, medium and low volume roads which are representative of highway functional categories in Ontario. A framework involving all stakeholders should be developed to extend this study to all types of highways and the associated failure modes. Experiments should also be considered to be taken in the spring when pavements are relatively weak. The impact of using SWB on other potential pavement surface damages such as top-down cracking or rutting should also be assessed.

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LIST OF TABLES

Table 1 Comparison of contact stress for SWB and dual tires

Dual tire 11R22.5			SWB - 455/55R22.5		
Load kg	Net contact area mm^2	Stress kPa	Load kg	Net contact area mm^2	Stress kPa
5500	36791	1467	5100	32440	1542
5025	35141	1403	4085	29555	1356
4550	35740	**1249**	3500	29037	1182
6100	38249	1565	**4540**	29683	**1500**

Table 2 Comparison of EASL for SWB and dual tires causing identical tensile strain

Tire Type	**Axle Load kg**	**ESAL**	**ESAL Ratio Dual / SWB**
SWB (455S)	9,000*	1.46	1
EALDT (Weak pavement)	10,700	2.84	1.95
EALDT (Strong pavement)	12,300	4.86	3.34

* 9,000 kg single axle load on SWB is equivalent to 10,700kg to 12,300kg single axle load on the dual tire.

Table 3 Comparison of allowable load repetitions for SWB and dual tires

Tire Type	**Axle Load kg**	**Minimum Tensile Strain 10^{-6}**	**Maximum Tensile Strain 10^{-6}**	**Average Tensile Strain 10^{-6}**	**Minimum N_f 10^8**	**Maximum N_f 10^8**	**Average N_f 10^8**
SWB	9,000	119	189	154	5.12	1.12	2.19
Dual	9,000	101	155	128	8.69	2.14	4.01
Fatigue Life Ratio (Dual tires /SWB tires)					1.70	1.92	1.83

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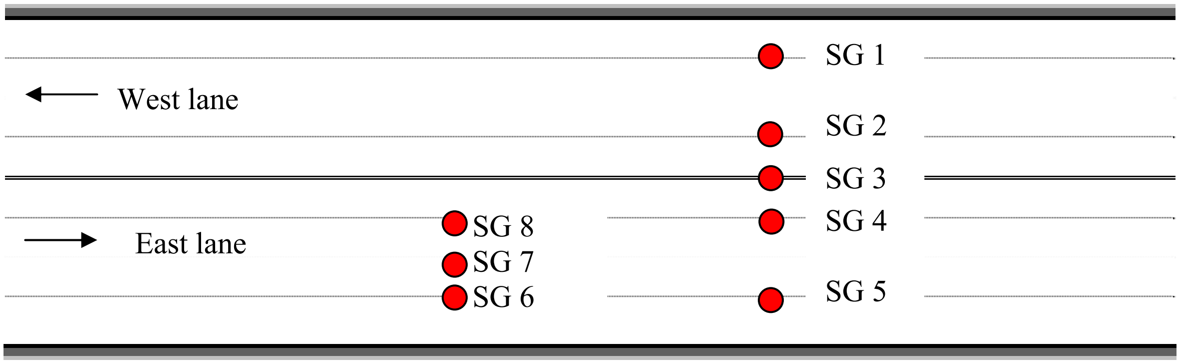


Figure 1 Plan view showing the location of asphalt strain gauges (SG)

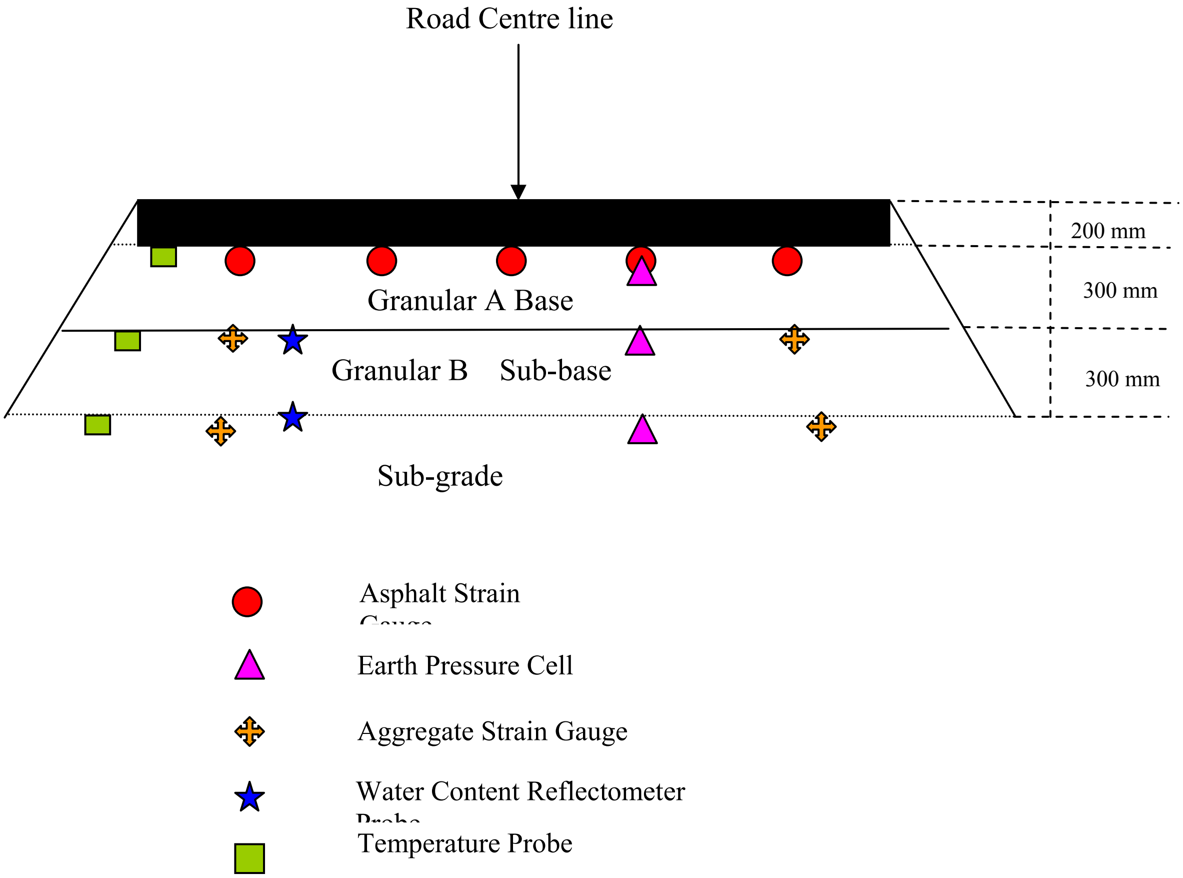


Figure 2 Cross-section view of the locations of different sensors in each layer

Figure 3 Liftable dual axles for testing dual and SWB tires

Figure 4 Sensor location with offset marking

Figure 5   SWB tire used in Phase 2 testing

Figure 6   Dual tire used in Phase 2 testing

Figure 7 Taking off-set measurements – Phase 2 testing

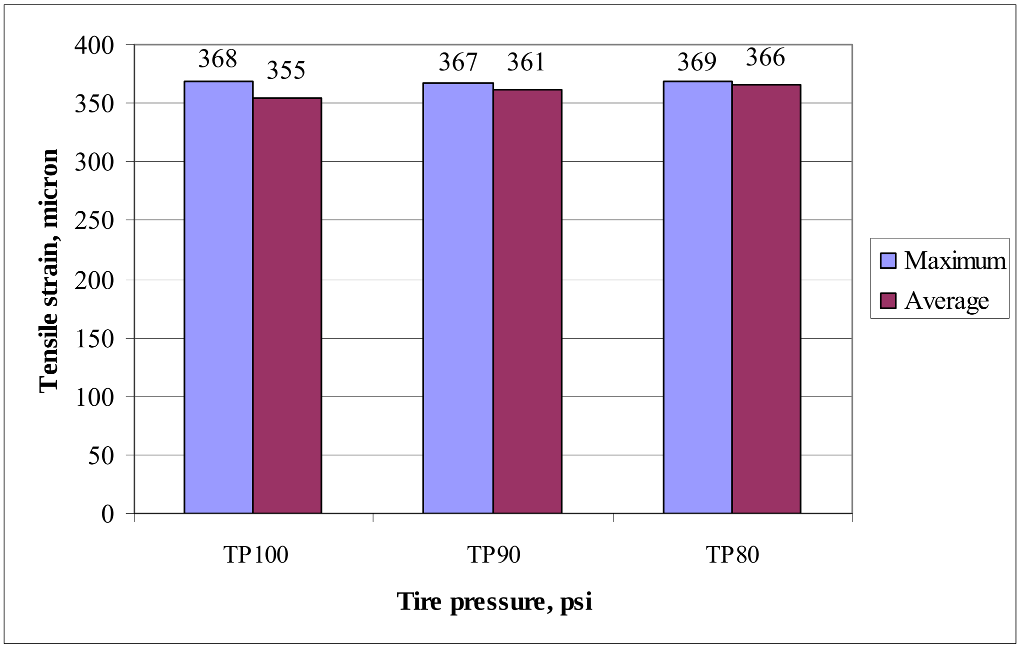


Figure 8 Effect of unequal tire pressure on tensile strain

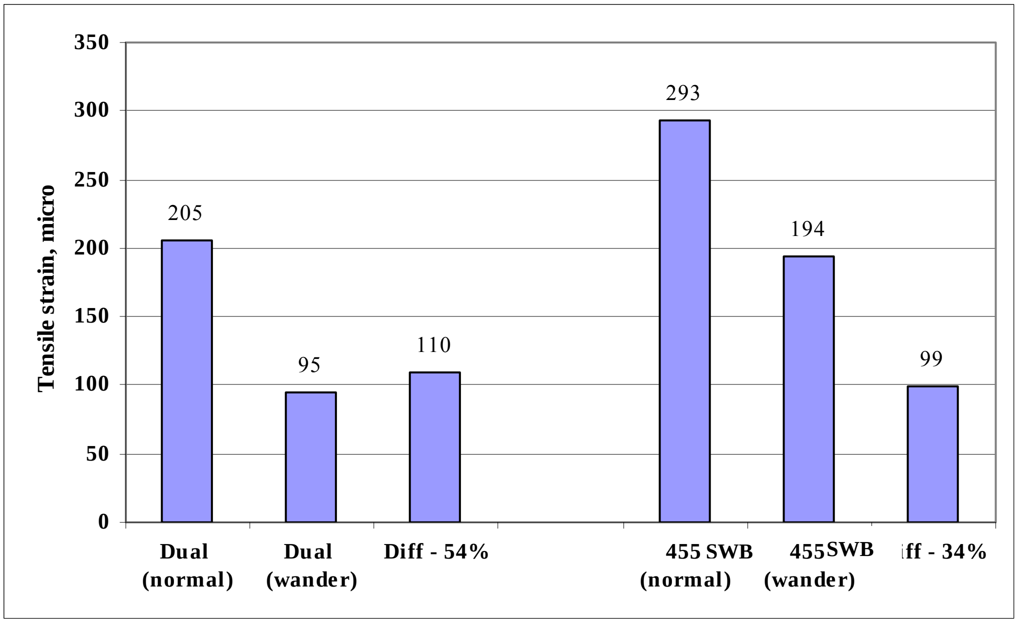


Figure 9 Effect of wander on tensile strains

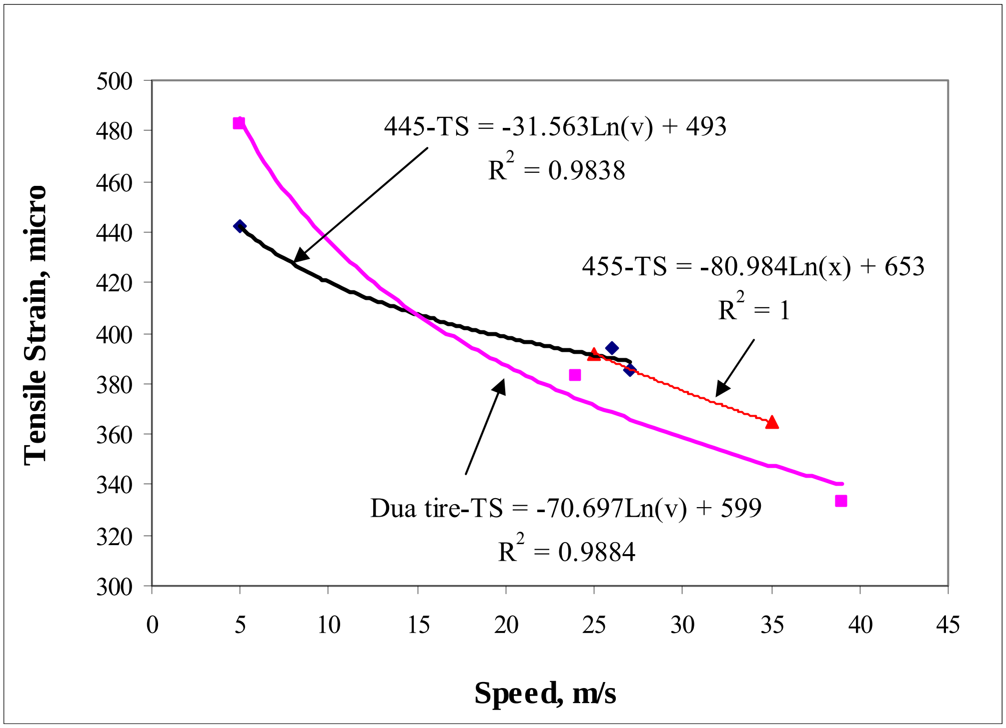
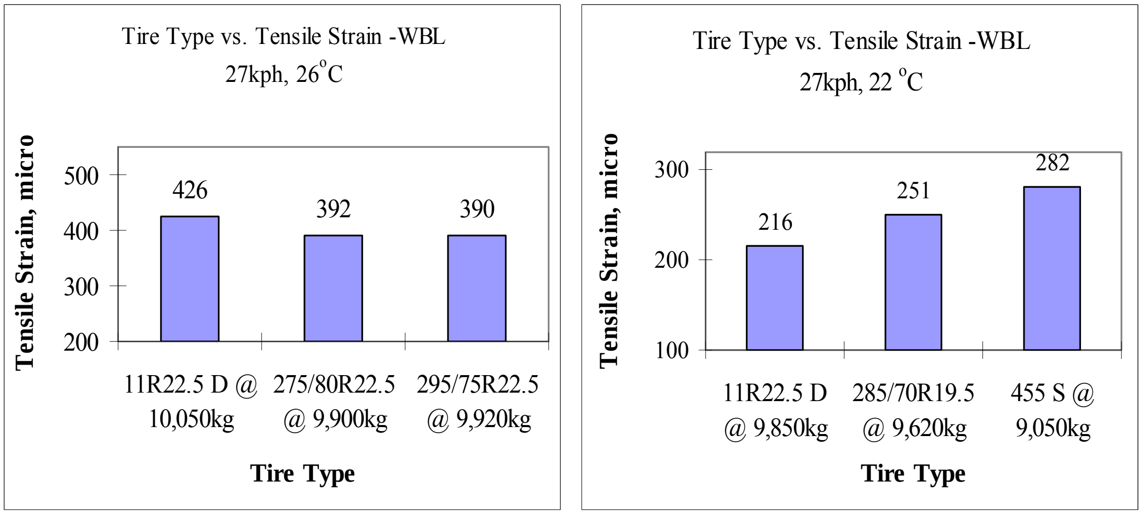


Figure 10 Effect of speed: Dual vs. SWB tires



(a) (b)

Figure 11 Influence of different tire types on tensile strain (WBL-Westbound lane)

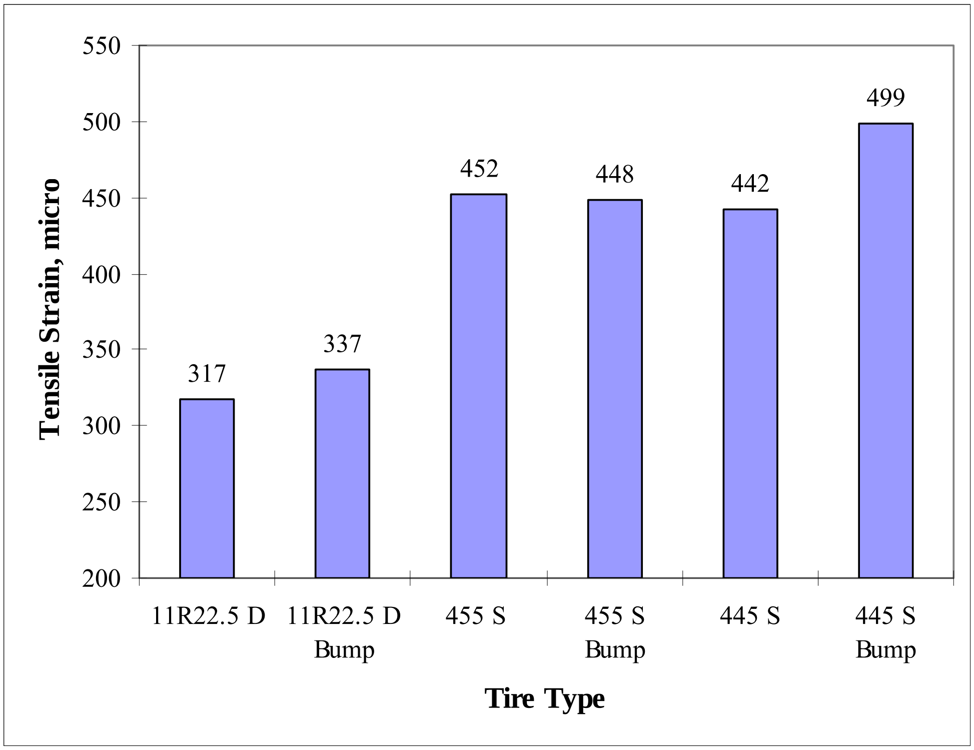


Figure 12 Tensile strains under dynamic loading for different tires at 22°C sub surface temperature

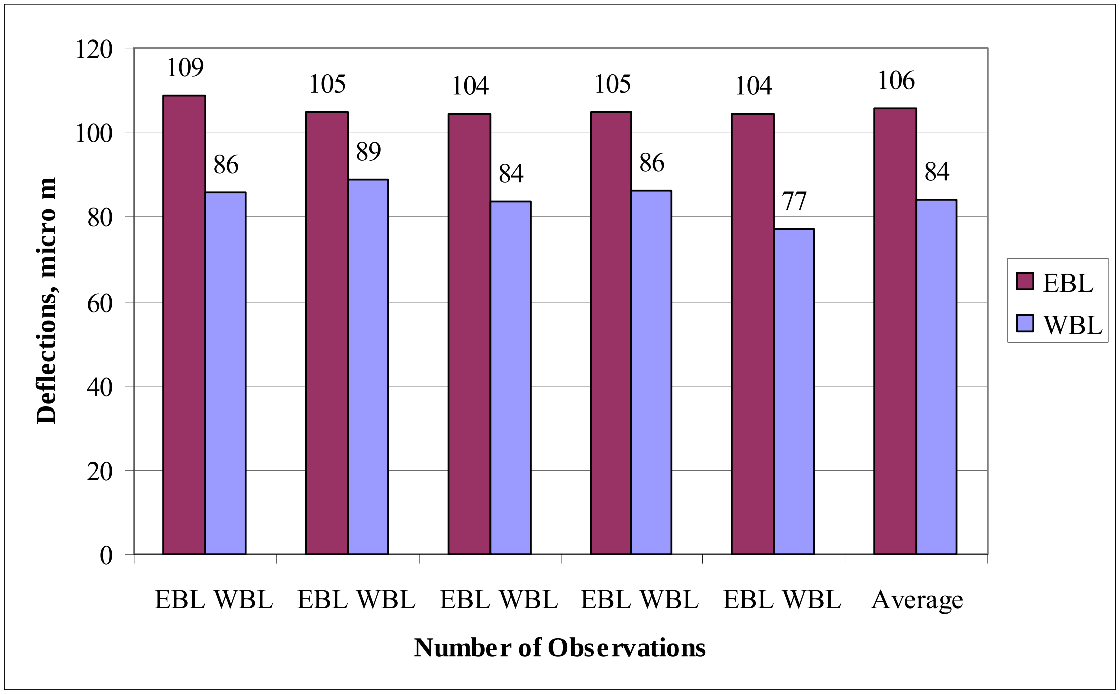


Figure 13 FWD Measurements: EBL vs. WBL

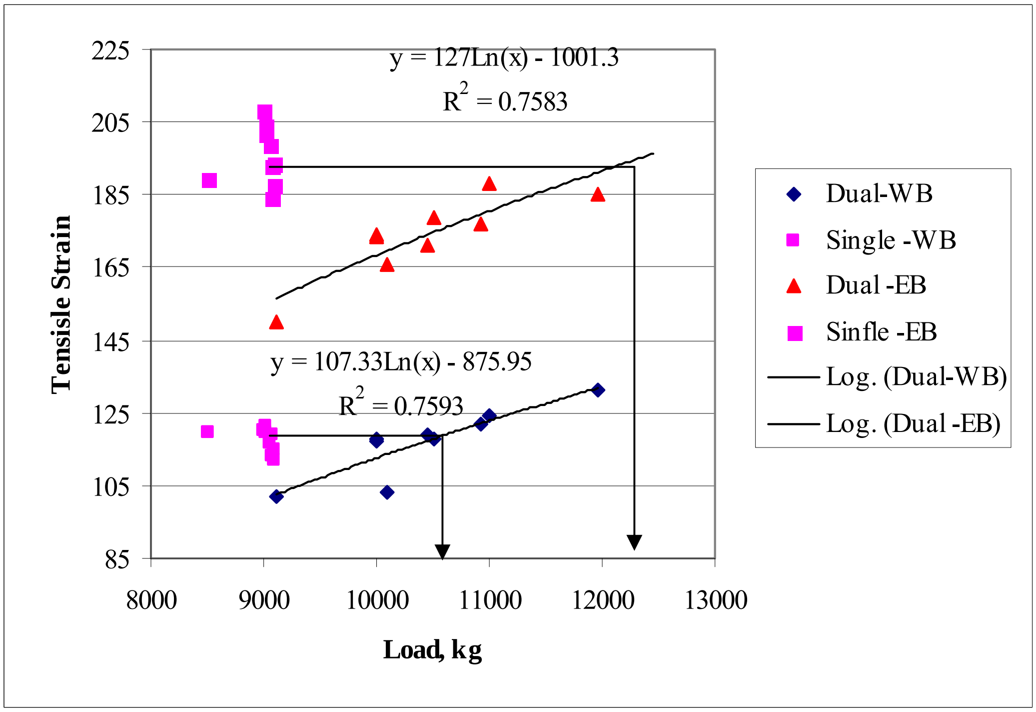


Figure 14 Axle load vs. tensile strain for dual and SWB tires for both lanes