Effect of tire type on strains occurring in asphalt concrete layers

Grellet D., Doré G., & Bilodeau J.-P.
Department of Civil Engineering, Laval University, Québec, Canada

ABSTRACT: The three main causes of road deterioration are the traffic, heavy loads and climate, and especially their interaction. The main objective of this study is to evaluate the impact of the tire type on the strains occurring within the asphalt concrete layer of a typical pavement structure. In an attempt to measure strains, an optic fiber instrumented polymeric plate was installed on the 100 mm section of the Laval University Experimental Road Site (SERUL). An innovative instrumentation technique has been developed in order to obtain transversal and vertical strain measurements at several levels within the asphalt concrete layer. Tests were performed to compare the effect of wide-base tires to the standard dual tires at standard tire pressure. Significant strain basin differences were measured between the two tire types. Especially for the dual tires, at the bottom of the layer, a compression zone was observed between the tire spacing. Several critical zones, in terms of strains, were identified near the tires edges and at the tires center which suggest that important shear phenomenon occurs at different level of the layer. The optic fiber instrumented polymeric plate will allow analyzing this phenomenon.

KEY WORDS: Flexible pavements, optic fiber strain gauges, dual and wide tires, transversal strain, strain basin.

1 INTRODUCTION

Flexible pavement response is affected by pavement design, asphalt layer properties, tire characteristics, applied load, temperature and vehicle speed. Compared to conventional dual tires, wide-base tires provide substantial benefits to trucking operations (Al-Qadi and al. 2007) especially in terms of fuel efficiency, hauling capacity, tire cost and maintenance. Previous studies on the pavement induced damages from the use of such tires were performed in the last few years. Some variability is noticed depending of the pavement damage criteria. Linear multilayered elastic models are frequently used for pavement design and analysis. An analysis using such theory predicts that fatigue life with the wide-base is reduced by 69% compared to the dual tires (Priest and al. 2006). However, during experimental work, the tensile strain measured at the bottom of the asphalt concrete layer is not significantly different between the two tire configurations. A three-dimensional finite element model concluded that the 445/50R22.5 tire causes more damage than conventional dual tires, reflecting an increase in fatigue cracking (Elseifi M.A. et al. 2005).

Several investigations concluded that the new generation of wide–base tires reduces rutting and top-down cracking damage. Pierre and al. (2006) suggested that the induced surface stresses and critical shear strains at shallow depth in the asphalt layer must be included as damage factors in the flexible pavement design methods. Some phenomenon, other than tensile strains at the bottom of the asphalt concrete layer, should be taken into account in the complex stress-strain scheme occurring within pavement bounded layers. The tension/compression phenomenon occurring near the asphalt concrete surface and the shear stresses occurring at the tires edges still need to be characterized precisely. The evaluation of the tire characteristics impact on flexible pavement structures would be more relevant if a combined damage ratio was used (Prophète 2003). The knowledge of the strain basin under the entire width of the tire at different layer depths is one of the main conditions for tire impact estimation.

The first goal of this project is to measure the strain evolution at different depths within asphalt concrete layers and to determine the entire strain basin under the tires for two typical tire types. This research project is part of Laval University NSERC industrial Research Chair i3C on the interaction between loads, climate and pavements.

2 INSTRUMENTATION

2.1 Laval University Experimental Road Site (SERUL)

The tests took place at the SERUL (Laval University Road Experimental Site) located at the Montmorency Forest. The test site was built in 1998 in order to study pavement behaviour under realistic conditions and controlled loading. It is located on the forest road 33, which crosses the road 175 at the kilometre 103. This large scale pavement laboratory was built to study surfacing materials, pavement behaviour for various conditions (materials, drainage and climate) and heavy vehicles effects on experimental embankment materials (HVE section). This HVE section is 100 m long and was used for the present study. The pavement structure at this location consists of the following layers: 100 mm hot mix asphalt (HMA), a 200 mm granular base (MG-20), a 480 mm granular subbase (MG112) and more than 1370 mm of silty till (natural soil). The test section was instrumented in July 2009 and tests took place in early October.

2.2 Strain sensors

In order to quantify the strains occurring at different depths within the bounded surface layer, an innovative 500x100x5mm instrumented plate was used (figure 1). This plate has been designed with polyphenylene sulphide (PPS) having an elastic modulus similar to asphalt concrete, allowing both materials to mechanically behave in a similar manner. For typical fall temperatures (season of experimental testing), the plate modulus is approximately 3,000 MPa. Different properties are summarized in table 1.

Table 1: Polyphenylene sulphide properties

Compressive Modulus	2.96 GPa	ASTM D695
Coefficient Thermal Expansion, linear 68°F	50.4 µm/m °C	ASTM E831

This plate was positioned inside a saw cut (8 mm) in the road and fixed with surrounding epoxy resin (film of 1.5 mm on each side). The groove width is minimal in order to minimize the asphalt concrete layer disturbance. The plate is instrumented with 24 optical fiber sensors located at various positions and levels. Eight sensors are placed horizontally at the top of the plate 20 mm below the plate surface (sensor N°1 to 8). Eight sensors are positioned vertically 5 mm under sensors 1 to 8 (sensor N°9 to 16). Finally, sensors N°17 to 24 are positioned horizontally at the bottom of the plate 95 mm below the plate surface. In order to measure the strain in two directions, the plate was installed perpendicularly relating to traffic direction. The sensors oriented in the X direction measure the transversal strain while those oriented in the Z direction measure the vertical strain (figure 2). Fiber-optic sensors are temperature independent, insensitive to transversal strain and their design is miniature. This technology enables to fix a sensor each 50 mm.

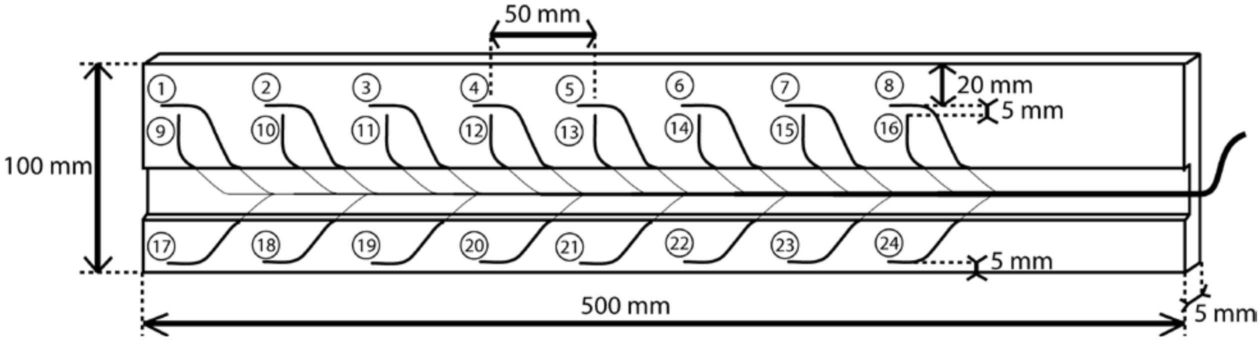

Figure 1: 100 mm instrumented plate design

2.3 Secondary sensors

As complementary data to the strains measurements, a temperature/water content transducer as well as a multi-depth water content transducer were used to monitor these significant parameters. The temperature measurement will give the asphalt concrete temperature, which is important to take into account considering the temperature sensitivity of asphalt concrete modulus. To minimize thermal variations, thermal blankets were installed in the morning before each tests day in order to keep asphalt concrete temperature at 8°C. Since asphalt concrete modulus is temperature sensitive, a variation of ± 2°C was tolerated. The blankets, which are connected to thermal baths, are removed from the pavement surface just before the truck passage and replace immediately after. This procedure allowed keeping the asphalt concrete temperature quite constant. The temperature/water content transducers are positioned near the sensors, but outside the wheel path to ensure that these sensors cause no disturbance on the results (figure 2).

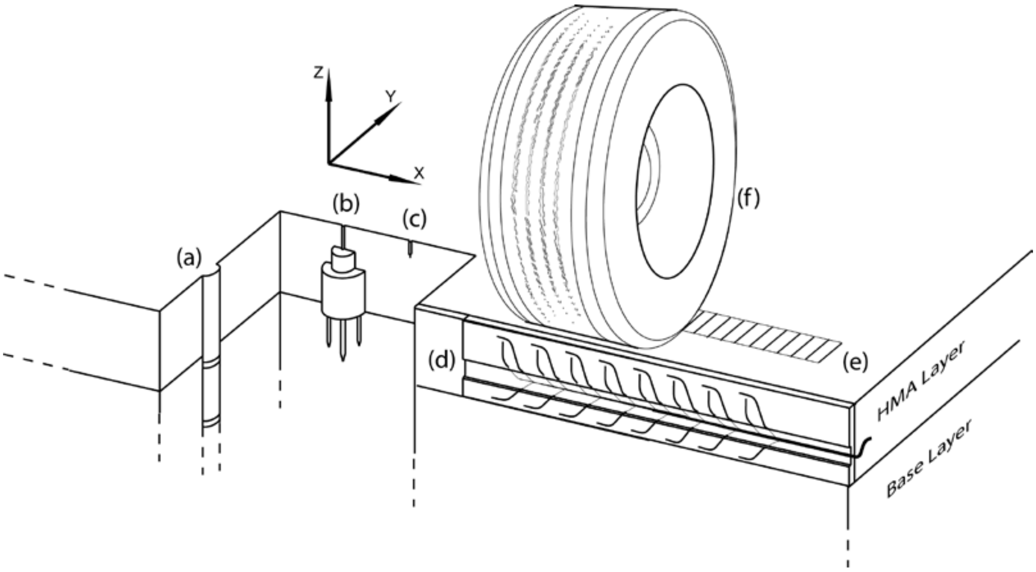

Figure 2: On-site instrumentation position. (a) multi-depth water content transducer, (b) water content sensor (road base), (c) asphalt temperature sensor, (d) instrumented plate, (e) visual positioning system, (f) tire.

3 METHODOLOGY

3.1 Test vehicle

The tests were conducted using a six axles vehicle (steering axle, two-axle drive and a trailer equipped with a three axles tridem). The truck was loaded with concrete blocks, which were positioned on the trailer to obtain a 80 kN standard load on the rear tridem axle.

3.2 Experimental protocol

In order to study the tire type effect on the flexible pavement response, the conventional dual tires 11R24.5 type was compared to wide base tires 455/55R22.5. The tire inflation pressure is maintained at a standard pressure of 100 psi for both type. The vehicle speed during the tests was 30 km/h. Preliminary tests were performed to evaluate the performance of the instrumentation and the influence of the tire type. During these preliminary tests, it was noticed that transversal strain variation is high near the edge of the tires. Therefore, in order to ensure the results quality, a visual positioning system was installed and all the passage are recorded on video. The video is consulted image per image to precisely identify the position of the tire with respect to the sensors. The visual positioning system is positioned near the plate axe to precisely measure the distance of the tire from the sensors (figure 2-e). In order to obtain a precise quantification of the strain basin under the tires, several passages are performed with various tire offsets in the X direction. The data acquisition is performed at 500 hz using a RadSens apparatus. The steering and driving axle tires and the load configuration on the truck remained unchanged during all the tests. The tire effect is evaluated by measuring the strain caused by the tridem equipped with the two different tire configurations.

3.3 Signal treatment

The vehicle passage results in strain (µε) versus time (s) graphs showing the sensors response to loading. A data point is measured and recorded every 2 ms. Moving average is applied to the data and each of the six strain values of the truck axle is identified and analyzed. To obtain the strain, the difference between the maximum strain of the axle and the zero load value recorded between each axle group is calculated as shown in figure 3. Software was specially designed for this purpose.

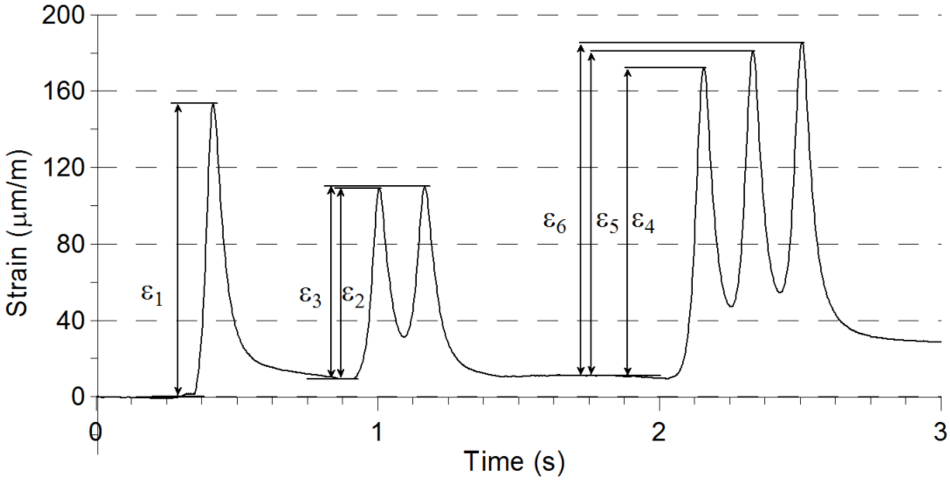

Figure 3: Strain amplitude ε_i measurement (i = axle number)

4 PRESENTATION AND ANALYSIS OF THE RESULTS

In this paper, the results obtained for the upper and lower transversal sensors are presented (sensor 1 to 8 and 17 to 24). In order to analyze the tire type effect, the three tridem axles are isolated from the entire signal. Finally, to plot the strain basin, only the first axle of the tridem is used.

4.1 Lower and upper transversal strains in the asphalt concrete layer

Depending on the sensor position with respect to the tire (center or edge), two characteristic signals can be obtained as shown in figure 4. For all the sensors, the signal shapes are similar to the signals measured by other types of strain gauges (Chenevière 2005). Under the tire, upper transversal sensors response is negative which is associated with a compression zone. On the opposite, lower sensors present a positive response which is associated with a tension zone. Therefore, a strain inversion takes place somewhere between the two instrumented levels within the asphalt concrete layer. Outside the tire, the same conclusion can be made since the upper sensors response is positive and the lower sensors response is negative. The typical signal shapes presented in figure 4 are similar for both tire types. However, the X position has the more pronounced influence on the strain amplitude. Indeed, the strain sign changes depending on the position under the tire. Near the tire's edge, there is a transition from tension to compression 20 mm below the surface, and from compression to tension at the bottom of the layer.

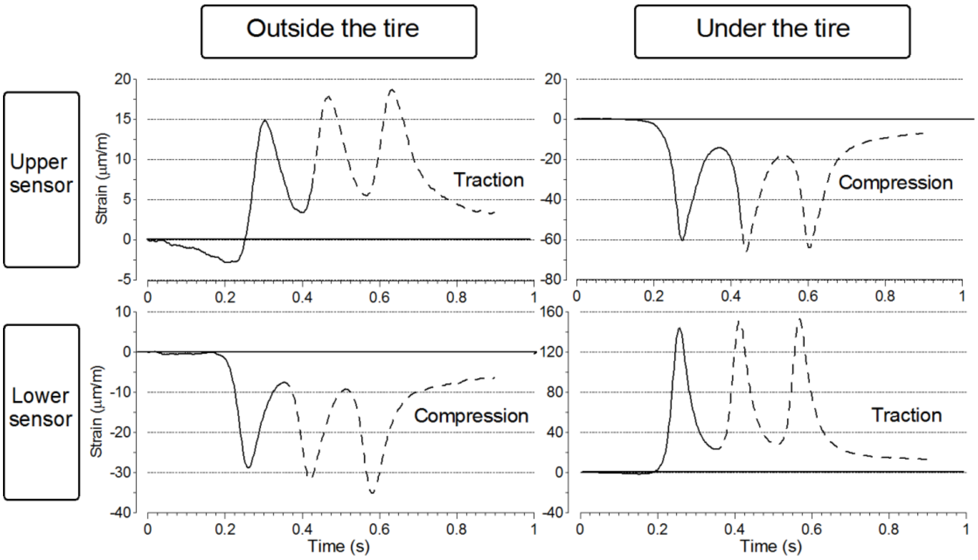

Figure 4: Characteristic signals from transversal sensor

In order to better understand this phenomenon, the entire strain basin was determined by taking measurements at progressively increasing tire offset from the edge of the tire. In order to investigate on the tire type, the analysis will be performed on the first tridem axle only. This approach allows eliminating the influence of the second and the third axle (dash line in figure 4). Different repeatability tests were performed and comparisons between sensors at the same position under the tire were done in order to evaluate the results reliability.

4.2 Results confidence

In order to analyze the repeatability of a strain measurement with a specific sensor, several test series having the same tire offset are selected. The difference, expressed as percentages and micro-strains between the axle strain amplitudes, is calculated for each sensor. Then the average difference and standard deviation are calculated in percent and µε (Table 2). The second analysis consists in a strain comparison between various sensors at equivalent tire offsets, repeating the calculation for different tire offsets. This explains the larger number of samples used for this comparison between the sensors.

Table 2: Sensors repeatability and comparison

Upper sensor	Average difference		Standard deviation		Number of value	Range of value
Sensor repeatability	6.22%	2.49 µε	3.76%	1.64 µε	28	[-75 µε ; 45 µε]
Sensor comparison	12.73%	6.47 µε	11.12%	6.35 µε	76	
Lower sensor	Average difference		Standard deviation		Number of value	Range of value
Sensor repeatability	2.48%	3.38 µε	1.70%	2.24 µε	25	[-70 µε ; 170 µε]
Sensor comparison	6.07%	7.87 µε	4.70%	5.49 µε	79	

Since the lower sensors strain amplitude is higher than the upper sensors, the analysis expressed in percentages is more significant. Difference of 7% is typically found between two similar measurements on the same sensor. Thus, it can be concluded that the sensors signal is reliable. Nevertheless, some differences still exist between the upper and the lower sensors, in terms of sensor repeatability, which may be explained by offset precision during the test. As stated by Grellet and al. (2009), the upper sensors are more sensitive to tire offset. The differences found for the sensors comparison is explained by several factors. Indeed, the gain of all sensors is different and the position of the sensor within the layer can influence the signal. As a matter of fact, the layer heterogeneity has an impact on the signal. For example, the presence of an aggregate near the sensor can increase the local modulus and reduce the strain amplitude. In dense-grade asphalt mixture, most of the sensors are located near aggregate particles, so the impact remains minimal (around 5% for the lower sensors and 12% for the upper sensors).

4.3 Strain basin

In order to determine the strain basin under the tires, measurements at progressively increasing tire offset (X position) were performed. The four strain basins (two for each tire type) are presented in figure 5. The tires position and edges are also represented.

When looking at the obtained results for the lower sensors, the transversal strain curve shows a maximum value of 155 με at tire's center for the wide base tire. For the dual tire, the strains reach two maximum values (143 με and 138 με) at the center of each tire. The strain caused by the dual tires reach a minimum value of -33 με at 260 mm of the outside tire's edge. The negative value means that, between the dual tires, the layer is under compression. The strain basins measured for the dual tires are also larger. As a matter of fact, the affected zone is more important due to the dual tires width. The tensile strain zone is 510 mm wide for the wide base tire. For the dual tires, this zone is 552 mm wide (285 mm and 267 mm). The maximum strain caused by wide base tires is higher to the ones induced by dual tires. However, it should be noticed that the strain variation is lower, which is explained by the fact that there is only two transitions from compression to tension for the wide-base tire. For standard dual tire, the bottom of the asphalt concrete layer is subjected to two additional sign inversions on a short distance between the tires (100 mm).

A similar analysis is performed for the upper sensor. The strain basin also seems symmetrical for each tire type. A maximum compression strain value (-58 με) is reached for the wide base tire. For the dual tires, the curve shows the first maximum strain at -43 με and the second at -41 με. For both tire type, the signal remains negative under the load (compression). However, the spacing found between the two tires (dual tires) causes a slight local strain reduction. The compression zone width is 550 mm and 740 mm for the wide base tire and dual tires respectively. The data scattering is important to notice for offsets higher than 400 mm, which is explained by road borders proximity.

The higher surface contact of the dual tires creates a better load dispersion. Also, near the tire edges, the wide base tire strain basin slopes are less pronounced. In addition, for dual tires, the signal shape under the tires spacing is particular. During the load passage, the strains are not only negative and the material is submitted to a complex tension and compression fatigue stress. The signal tension value is shown in figure 5 (cross symbols). More details are given in the next section of this paper.

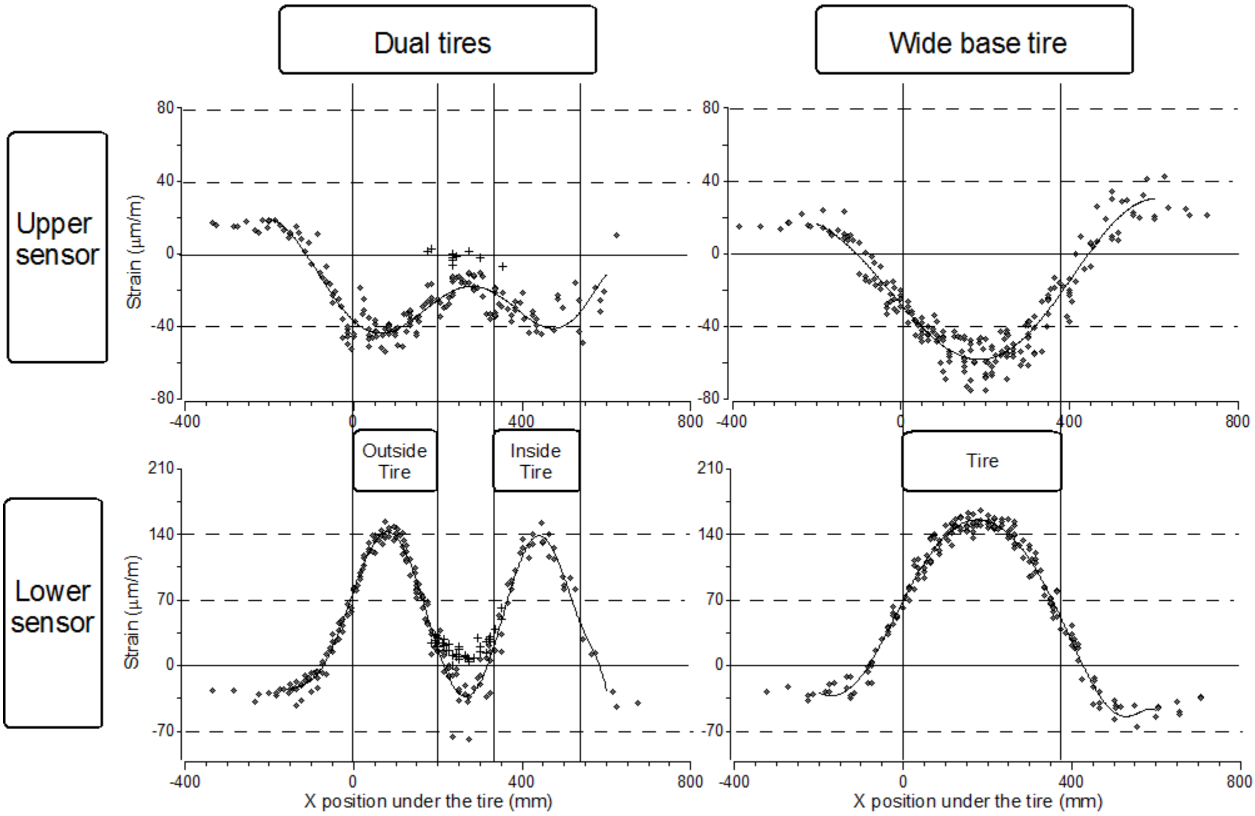

Figure 5: Transversal strain basins for dual tires and wide base tires

4.4 Signal evolution near the edge of dual tires

By selecting measurements at progressively increasing tire offsets, the transition from tension to compression under the dual tires spacing can be precisely analyzed for the lower sensors (figure 6). Near the edge of the tire, the signal shape dissents from figure 4. At 200 mm and 215 mm, the maximum strain values are not measured at the axle passage (corresponding to the axis of symmetry of the signal) but slightly before and slightly after. At increasing offsets, this phenomenon becomes more pronounced. At a specific tire offset, the applied load starts to impose a compression to the asphalt concrete, the 245 mm tire offset being a good example. During 0.08 second (from 0.146 to 0.224 second), a tension signal is recorded (maximum strain of 16.3 µε at 0.206 second). Afterwards, during 0.024 second (from 0.224 to 0.248 second), a compression signal is observed (maximum strain of -10.1 µε at 0.236 second). Finally, during 0.06 second (from 0.248 to 0.308 second), a tensile strain is measured again. The maximum compression strain value is reached at the middle of the spacing (275 mm). From upper offsets than 275mm, the phenomenon is symmetrical and the compression effect decreases. At 350 mm, the signal remains positive (tension). Therefore, the performed analysis suggests that, for standard dual tires loading, the bottom of the asphalt concrete layer is subjected to two different strain types (tension-compression-tension) during a very short load application time.

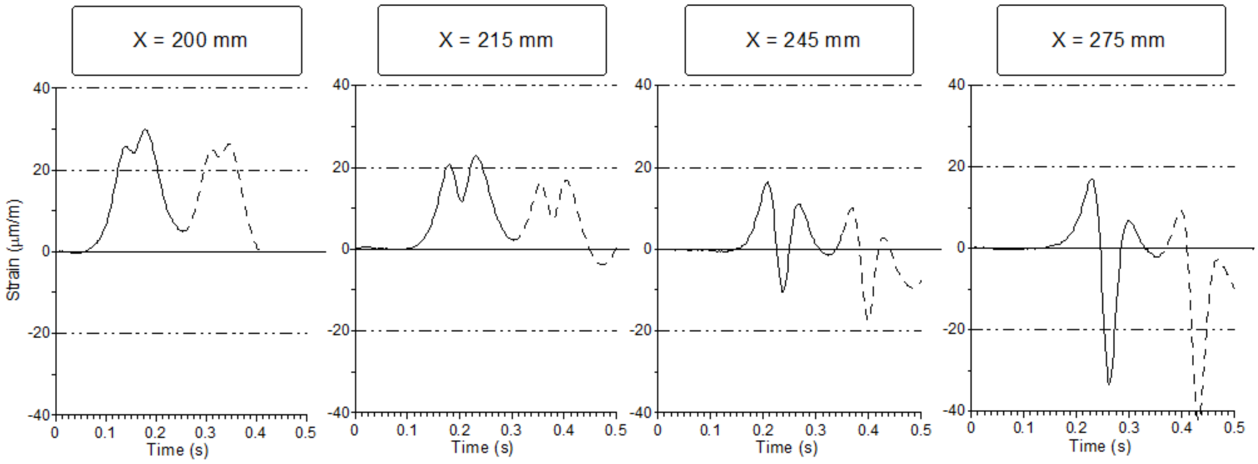

Figure 6: Transition from tension to compression for the first tridem axle with dual tires.

Similar signal have been identified near the outside edges of the tire (offset values of -100 mm and 600 mm for the dual tires, -75mm and 550 mm for the wide-base) due to the compression-tension transition. Near the layer surface, another phenomenon can be observed in figure 7 for the dual tires. The signal shape is reversed in comparison with the lower sensors. The signal remains in compression, but during the axle passage, the strain magnitude decreases before it increases again.

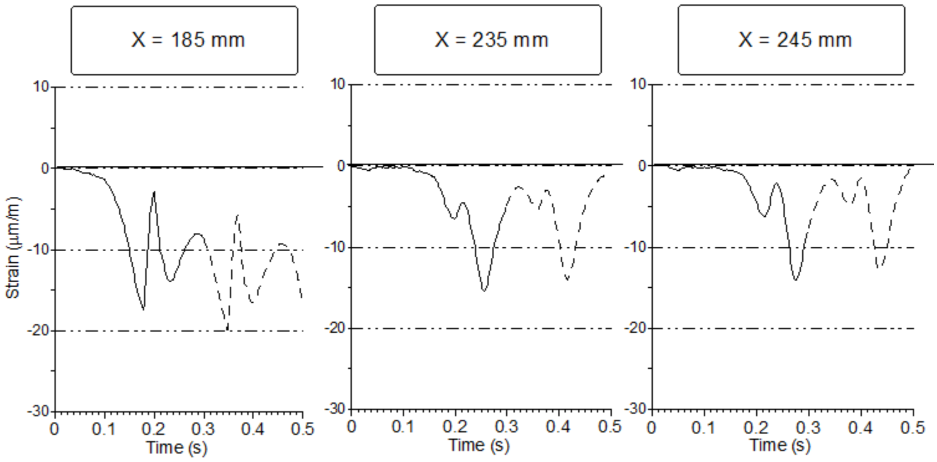

Figure 7: Near surface phenomenon observed for dual tires.

5 CONCLUSION

The goal of this investigation was to characterize the various compression and tensile strains occurring in asphalt concrete layers and to obtain the entire transversal strain basin for two tire types. Significant strain basin differences were measured between the two tire types. For the dual tires, a compression zone was observed between the tire spacing, the transition between tension and compression being progressive. Near the layer surface, this compression phenomenon is significantly reduced by the use of dual tires. Several critical zones, in terms of strains, were identified near the tires edges and at the tires center. As a matter of fact, for the standard inflation pressure tested, the maximum strains (tension and compression) were found at the center of the tire. However, near the tires edges, the strain signal changes abruptly from tension to compression which suggests that important shear phenomenon occurs at this level. The equipment used will allow proceeding to a detailed analysis of this phenomenon using the vertical sensors installed into the optic fiber instrumented polymeric plate.

REFERENCES

Al-Qadi, I. and M. Elseifi, 2007, *New Generation of Wide-Base Tires: Impact on Trucking Operations, Environment, and Pavements*. Transportation Research Record: Journal of the Transportation Research Board. 2008(-1): p. 100-109

Chenevière, Ph., Wistuba, M. & Dumont, A.-G. 2005. *Full-Scale Testing of Pavement Response by Use of Different Types of Strain Gauges*. Proc., 7th Int. Conf. on the Bearing Capacity of Roads, Railways and Airfields, 27-29 June 2005, Trondheim, Norway.

Elseifi, M. A., I. L. Al-Qadi, P. J. Yoo, and I. Janajreh., 2005, *Quantification of Pavement Damage Caused by Dual and Wide-Base Tires.* In Transportation Research Record: Journal of the Transportation Research Board, No. 1940, pp. 125–135.

Grellet D., Doré G., and Fachon J., 2009, *Étude comparative de l'impact des pneus à bande larges et des pneus jumelés sur l'interaction véhicule-route*, Research report for the Transportation Association of Canada, Laval University, Civil Engineering Department, Québec

Pierre P., Doré G. and Bilodeau, J.-P., 2006, *Strains at shallow depth in bound surfacing materials* 10th International Conference on Asphalt Pavement, 12-17 August 2006, Québec, Canada

Priest, A. and D. Timm, 2006, *Mechanistic Comparison of Wide-Base Single versus Standard Dual Tire Configurations.* Transportation Research Record: Journal of the Transportation Research Board, 1949(-1): p. 155-163.

Prophète, F. 2003, *Effets de différents types de pneu sur les chaussées.* Project No 5.2R456.1 Quebec minister of transportation, Direction laboratoire des chaussées, Québec, Canada.