Measured tire/road contact stresses
characterized by
tire type, wheel load, and inflation pressure

Robert A. Douglas, BASc(CE), PhD, PEng
Senior Geotechnical Engineer, Low-volume Roads
Golder Associates Ltd., Mississauga, Ontario
(corresponding author : RDouglas@Golder.com)

David Alabaster, BE (Hons) ME (Civil)
CAPTIF Manager, Engineering Policy Section
Transit New Zealand, Christchurch, New Zealand

Neil Charters, BSc (Hons), ME (Civil)
Geotechnical Engineer
Golder Associates Ltd., Christchurch, New Zealand

Paper prepared for presentation at the

Introducing Innovation into Pavement Design and Rehabilitation

Session

of the

2008 Annual Conference of the
Transportation Association of Canada
Toronto, Ontario

Measured tire/road contact stresses, characterized by tire type, wheel load, and inflation pressure

Robert A. Douglas, David Alabaster, and **Neil Charters**

Abstract

The road engineering community sees the increased use of recycled and marginal pavement materials as a key factor for more sustainable use of dwindling resources. However, successful use of alternative materials requires reliable models of pavement response and performance. In turn, these models depend on the accurate portrayal of tire/road contact stress distributions. Unfortunately, while the models have developed substantially, the acquisition of real stress distributions measured at full scale has not kept pace with the sophistication of the models.

To solve the problem, it was recognized first that the measurement of tire/road surface contact stress distributions in all three of the vertical, longitudinal, and transverse directions needed to be facilitated. Second, a wide range of measured stress distributions needed to be used as input to models of pavement response and performance being developed.

A multiphase project was conceived, to include (1) building an apparatus to measure contact stresses under full scale tires, (2) measuring contact stresses for a range of tire types, wheel loads, and inflation pressures, (3) characterizing the contact stresses as a function of tire type, wheel load, and inflation pressure, and (4) using the measured contact stresses as inputs to numerical models of pavement response and performance currently under development.

The paper discusses the first three phases of the project.

Introduction

It is becoming widely known that resources needed to construct pavements and roads are not infinite, and are beginning to dwindle rapidly in some locations. The road research, design, construction and administration community sees the increased use of recycled and marginal pavement materials as a key factor for more sustainable use of these dwindling resources. However, successful use of alternative materials requires reliable models of pavement response and performance. In turn, these models depend on the accurate portrayal of tire/road contact stress distributions. Unfortunately, while the models have developed substantially, the acquisition of real stress distributions measured at full scale has not kept pace with the sophistication of the models.

Currently, pavement designers and modellers work primarily on the basis of the *forces* exerted by tyres on pavements, rather than *stress distributions*. Those who do account for stresses usually deal with only the vertical pressure, and it is most often assumed to be uniform, and equal to the tyre inflation pressure. Pavement response models (e.g. CIRCLY, finite element programs) do have the capability to accept as inputs non-uniform vertical, longitudinal and transverse stresses within the tyre contact patch, but this is rarely done as few appropriate records of *measured* stresses exist.

The Project

To solve the problem, a handful of researchers dating back to at least 1928 (Eckels, 1929) have devised apparatuses to measure contact loads and/or stresses, and carried out tests on tires. A summary of the research is provided in Golder Associates (2007).

it was recognized first that the measurement of tire/road surface contact stress distributions in all three of the vertical, longitudinal, and transverse directions needed to be facilitated. Second, a wide range of measured stress distributions needed to be used as input to models of pavement response and performance being developed.

A multiphase project was conceived:
Design and build an apparatus to measure contact stresses under full scale tires. To the authors' knowledge only two apparatuses are in intensive use world-wide. Both make use of strain-gauge technology, and the lead author is intimately acquainted with one of those two apparatuses.
Measure contact stresses for a range of tire types, wheel loads, and inflation pressures, spanning and extending the conventional ranges for each. Special attention was to be focussed on low inflation pressures, to support research others are doing on central tire inflation systems.
Characterize the contact stresses as a function of wheel type, wheel load, and inflation pressure. Examine stress distributions across the tire contact patch.
Use the measured contact stresses as inputs to numerical models of pavement response and performance currently under development.

The paper discusses the first three phases of the project.

Progress to Date

The apparatus to measure the contact stresses has been designed, constructed and calibrated. A suite of full scale, indoor loading tests has been carried out in Transit New Zealand's Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF), with two wheel types, two wheel loads, and two or three tire inflation pressures (Figure 1). At the time of writing, the primary analysis

Figure 1. CAPTIF facility. (photo: Transit NZ)

of the data was complete, and records of contact stress were available for single tyre wheels. Work on the primary analysis of dual wheel load data was underway, and input to pavement response and performance models was yet to come.

Construction and Calibration of the Instrument

The contact stress measurement apparatus consists of a strong steel box enclosing 25@5×5 mm steel pins arranged as vertical cantilevers in a closely spaced row across the width of the intended tire path (Figure 2). The pins protrude 1 mm through holes in a surface plate over which the tire rolls. They are equipped with electrical resistance strain gauges to measure vertical compression along their axes, and bending in the longitudinal and transverse directions, relative to the direction of travel of the tire.
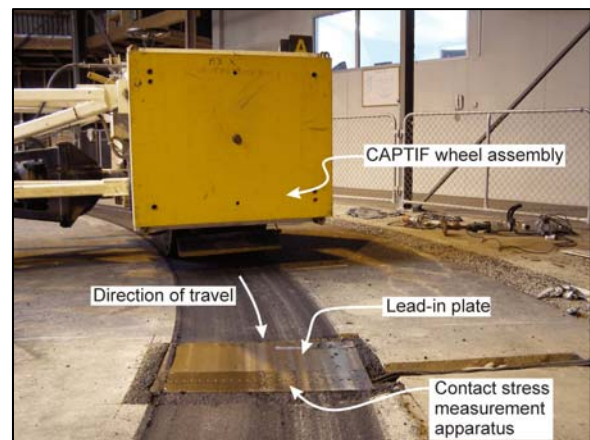

Figure 2. Contact stress measurement apparatus.

Each pin had six semi-conductor strain gauges installed in three pairs. The gauges in each pair were arranged opposite one another, and wired into a Wheatstone bridge in such a way as to sense compression or bending in the pin. The pins were loaded with a series of dead weights, the output recorded, and a linear regression derived in order to produce the required calibration coefficients (Figure 3). Each calibration was repeated at least 3 times. Bending calibrations were performed in opposite directions, and the regression coefficients averaged.

A high speed data acquisition system, capable of measuring any 8 channels of data at a rate of 10,000 samples per second, was assembled. The data was acquired on four pins at a time, with four pins measured in compression and two pins in both bending directions.
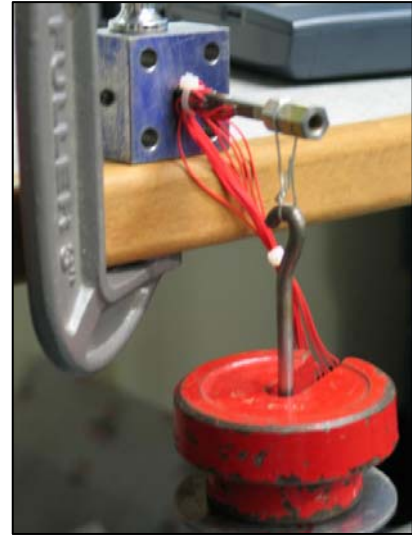

Figure 3. Pin calibration in bending.

Table 1 shows the matrix of test parameters studied. Two wheel types, two wheel loads, and two or three inflation pressures were used in the full scale load tests. At least five passes of the wheel was made at each combination of wheel load and inflation pressure.

Table 1
Load test combinations

Wheel type, tire designation	Wheel load	Inflation pressure or deflection (kPa or %)
Dual wheel 295/80 R225 M840	40 kN	690
		550
		20% (280 kPa)
Wide single 385/65 R225 R194		690
		550
	50 kN	690
		550
Dual wheel 295/80 R225 M840		690
		550
		20% (280 kPa)

Results

Tire patch lengths have been inferred from the data sampling rate and the speed of the tire running around the test track. The approximate contact patch lengths are given in Table 2.

Table 2
Approximate tire contact patch lengths

Wheel type, tire designation	Wheel load (kN)	Inflation pressure or deflection (kPa or %)	Approximate tire contact patch length (mm)
Wide single 385/65 R225 R194	40	690	310
		550	330
	50	690	310
		550	360
Dual wheel 295/80 R225 M840	40	690	220
		20% (280 kPa)	290

For selected all combinations of wheel load and tire inflation pressure tested, schematic plan views of the compressive, longitudinal and transverse pin loads are shown in Figures 4, 5, and 6. The plots show the pin load as a function of position within the tire contact patch. Longitudinal distances were calculated based on the sensor sampling rate and tire speed around the test track. Transverse distances were multiples of the pin spacing of 25 mm. The plots are not to scale: the longitudinal scale / transverse scale ratio is distorted.
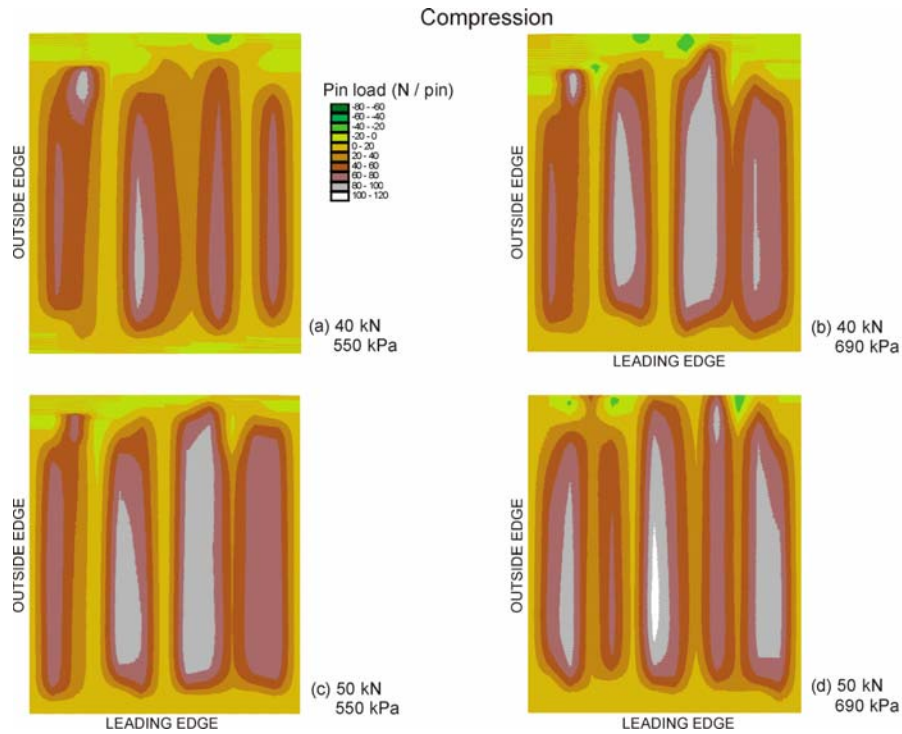

Figure 4. Schematic plan view of compression pin loads for single tires. Wheel loads (kN) and tire inflation pressures (kPa) are shown for each plot. (Not to scale)
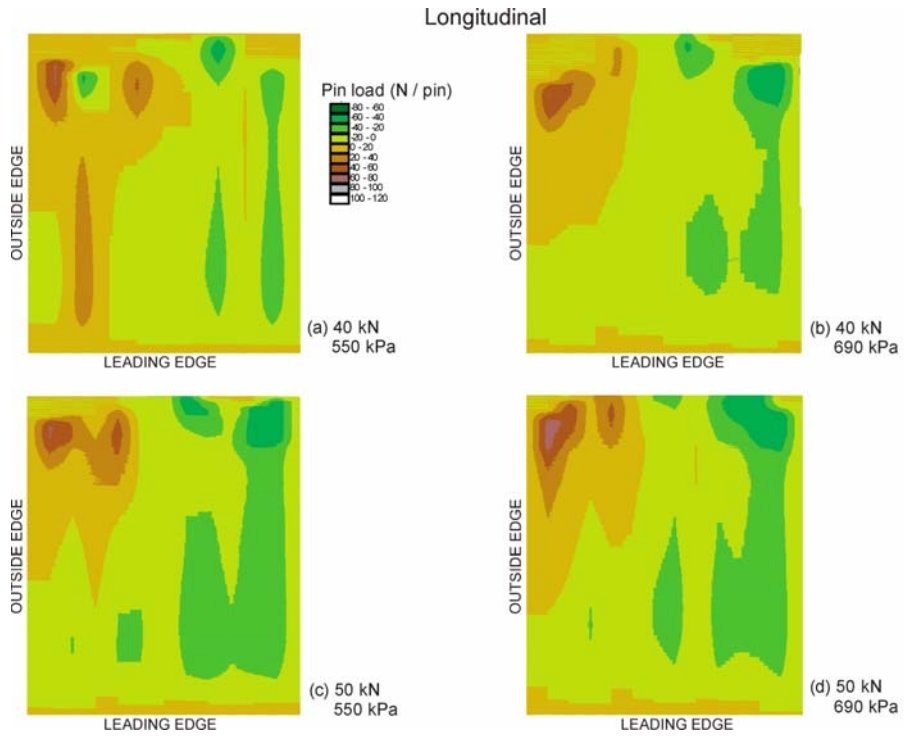
Figure 5. Schematic plan view of longitudinal pin loads for single tires. Wheel loads (kN) and tire inflation pressures (kPa) are shown for each plot. (Not to scale)
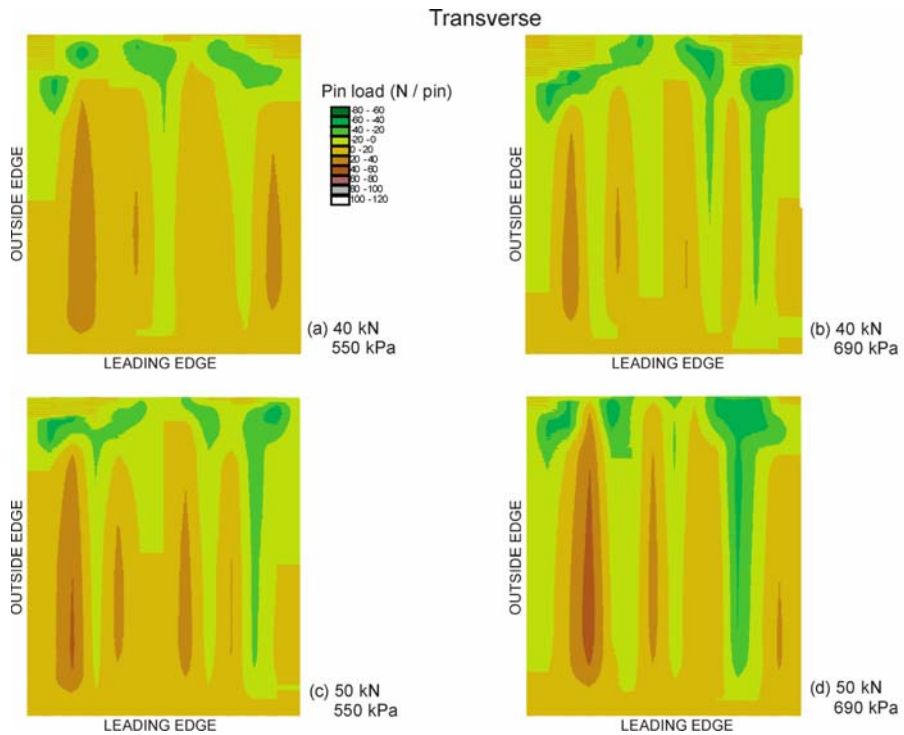
Figure 6. Schematic plan view of transverse pin loads for single tires. Wheel loads (kN) and tire inflation pressures (kPa) are shown for each plot. (Not to scale)
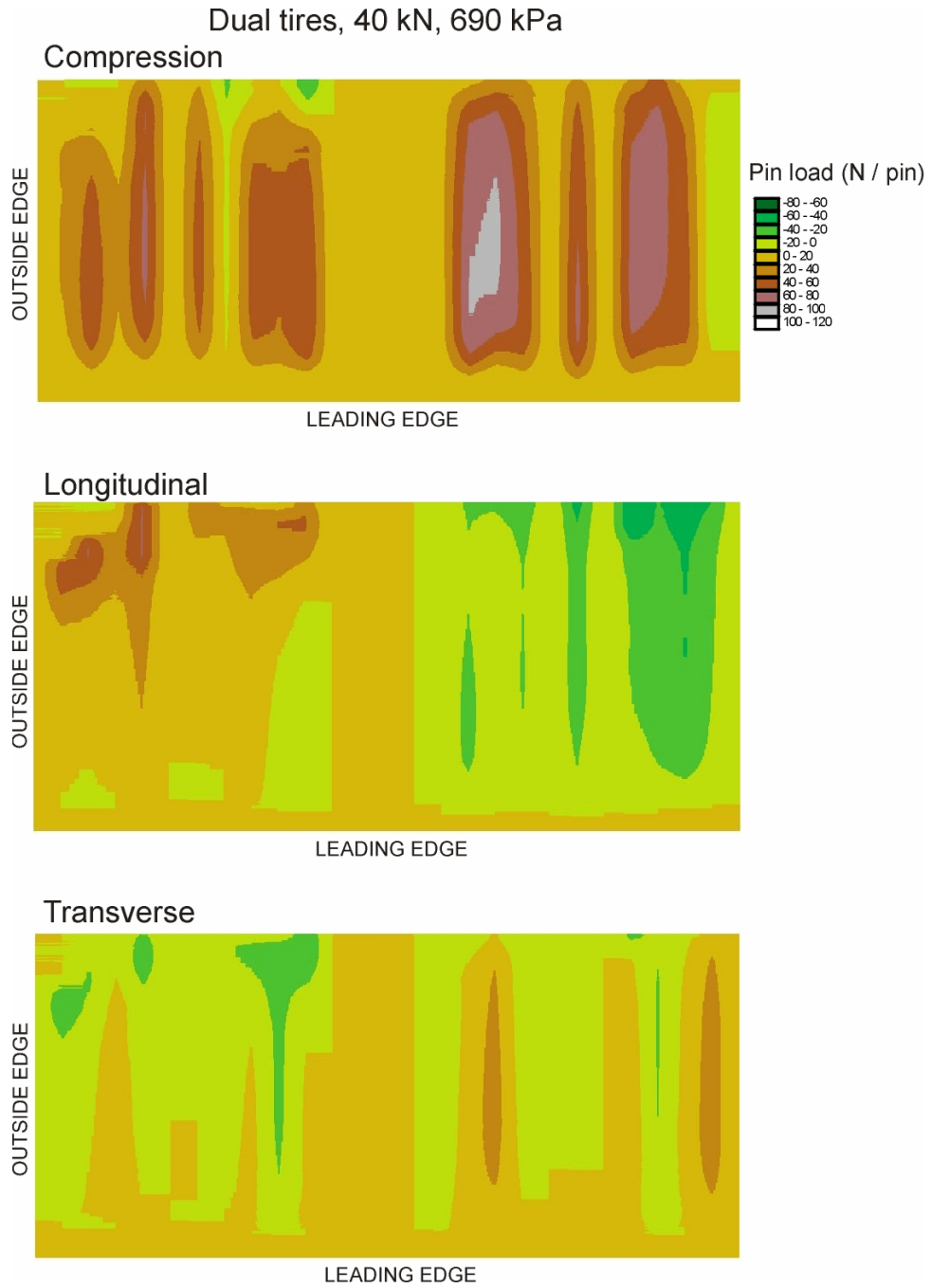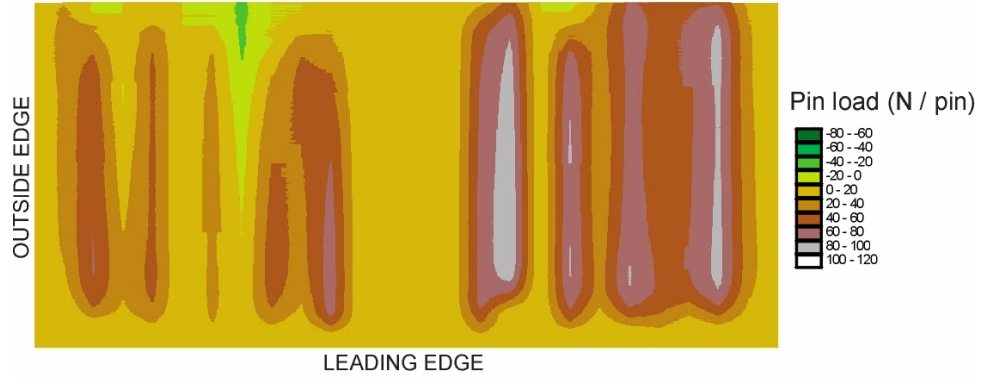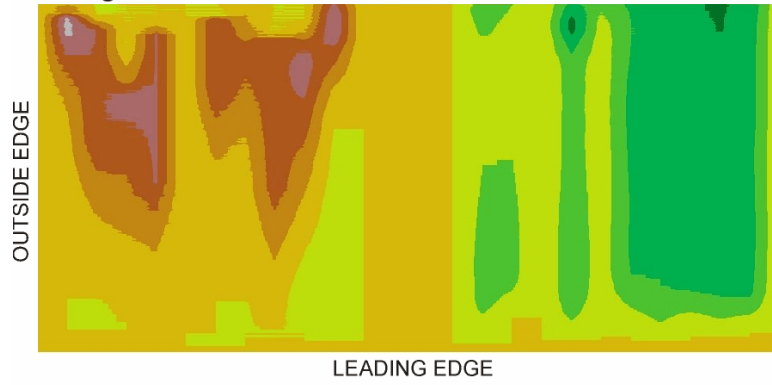
Figure 7. Schematic plan view of pin loads for dual tires: wheel load 40 kN, tire inflation pressure 690 kPa. (Not to scale)
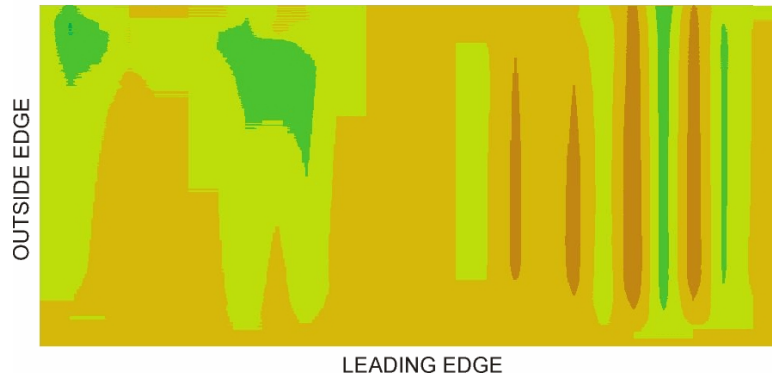
Figure 8. Schematic plan view of pin loads for dual tires: wheel load 40 kN, tire inflation pressure 280 kPa. (Not to scale)

The pin loads recorded depend on whether the individual pin contacted a tire tread block or happened to fall into a groove in the tread pattern, and the pin loads have been smoothly interpolated between pins. Therefore the pin load patterns shown are somewhat idealized from the real patterns, which would have been much more sharply defined.

Similar plots have been produced for selected dual tire wheel load and inflation pressures, Figures 7 and 8. The 40 kN / 690 kPa combination is typical of real trucks, whereas the 40 kN / 280 kPa is typical of the settings trucks using variable tire inflation systems would use.

Discussion

Contact Patch Length

The limited data available on the contact patch length agreed with earlier studies and general experience. Contact patches lengthened for increases in wheel load, and decreases in inflation pressure. For the four tests conducted, the contact patch length for the single tire was slightly more sensitive to inflation pressure than wheel load, with an increase of 25 % in the wheel load causing a 9% increase in contact patch length, but a 20% decrease in inflation pressure causing a 6 to 16% increase in contact patch length.

Contact Stresses, Sensor Pin Loads

It is important to make the distinction between real tire/road contact stresses (kPa) and the measured compressive, longitudinal, and transverse pin loads (N/pin). Figures 4-8 show the forces the tires imposed on the pins. The real contact *stresses* are indeterminant: the pins protruded 1 mm above the level of the apparatus bed plate over which the tires ran, the pins shared the stresses imposed by the tires with the adjacent bed plate surface, and the area of the tire lifted and supported by each pin cannot be determined. However, the distributions of the loads on the pins can be taken as indicative of the real contact stresses.

Single Tires, Compressive Pin Loads

As shown by Figure 4, the compressive loads on the pins were affected by the inflation pressure and the wheel load. As either increased, the peak compressive pin load increased. The maximum pin load for any of the four combinations of wheel load and inflation pressure tested was of the order of 120 N.

Single Tires, Longitudinal Pin Loads

For the single tire tests, the longitudinal loads on the pins did not follow the S-shaped pattern, running front to back through the tire contact patch, that had been observed by others (Lippman 1985; Tielking and Roberts 1987; Siegfried 1998, Douglas *et al.* 2000). Figure 5 shows that there was a variation of the distribution across the *width* of the contact patch, with loads with a positive sense found towards the outside edge of the contact patch, and loads with a negative sense found towards the inside edge.

To understand the sense of the sensor output, reference should be made to Figure 9. Longitudinal
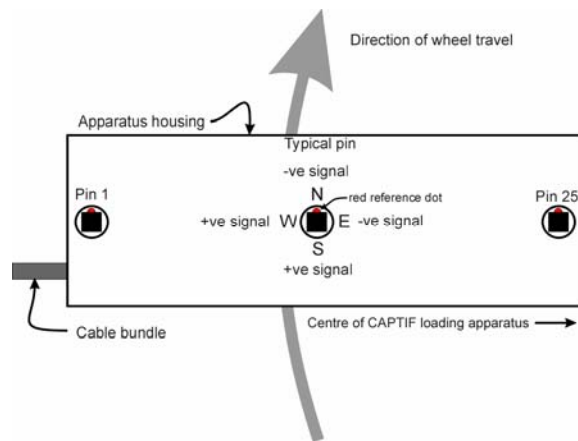

Figure 9. Schematic plan view of sensor apparatus.

and transverse sensor readings were positive or negative, depending upon which way the tire pushed the tip of the pin. The direction in which the wheel travelled needs to be taken account of, too.

Single Tires, Transverse Pin Loads

Again, as shown in Figure 6, there was a variation of the pin loads across the width of the tire contact patch. While there was some inconsistency in the pattern, generally, the transverse pin loads were positive towards the outside edge of the tire, meaning the pin were pushed pins toward the outside edge of the tire. The reverse was true at the inside edge of the tire. This was the opposite of what has been observed by others (Tielking and Roberts 1987; Douglas *et al.* 2000).

Pin Loads for Dual Tires

Two sets of pin load data for dual tires are presented in Figures 7 and 8. The 40 kN / 690 kPa wheel load / tire inflation pressure combination is typical of real trucks. The 40 kN / 280 kPa combination is typical of the same vehicle employing a reduced tire inflation pressure setting using a central tire inflation (CTI) system. The wheel load remains the same, but the inflation pressure has been drastically reduced to obtain the benefits of CTI, perhaps on an aggregate surfaced road.

In the two figures it can be seen that the compressive pin loads and therefore the tire loads were mismatched between the inner and outer tire, despite the careful control exercised in the test lab. Comparing the two figures, it can be seen that deflating the tires redistributed the compressive pin loads towards the outer edges of both tires, the expected trend (Marshek *et al.* 1986; de Beer *et al.* 1997).

The longitudinal pin load distribution across the dual tires mimicked the distribution across single tires (Figure 5), with a positive sense towards the outside of the pair of tires, and a negative sense towards the inside of the pair. Longitudinal pin loads were greater for the lower inflation pressure.

The transverse pin loads under the dual tires did not follow the trend established by the single tires. Pin loads generally had a negative sense towards the outside of the pair, and a positive sense towards the inside of the pair. As was the case for the longitudinal pin loads, the transverse pin loads were generally greater for the lower inflation pressure.

Tire Scuffing

The trends and magnitudes of the compression pin loads were as expected for both the single tires and the dual tires reported on here. However, the results for the longitudinal and transverse pin loads did not agree with previously-published results.

It must be noted that for the first time, contact stress-type data is reported for tests carried out on a circular track, rather than a linear test facility. Granted that the radius of the test arms at CAPTIF are large, at 9 m, there still is the possibility of tire scuffing caused by the continuous right-hand bend the tires are negotiating. In addition, there are issues of vertical tire load sharing, and the camber and effective toe-in that must exist. The tires may be under- or over-steering for the continuous bend in their path, thus causing differences in the longitudinal and transverse pin loads compared to what has been observed by others working on linear facilities with near-perfect alignment.

It may also be the fact that the data is incorrect.

The graphs of pin load distribution are the products of a long series of steps, and their results are a function of a list of interacting inputs, including:

- the arrangement of the strain gauges installed on the pins
- the arrangement of the pins in the apparatus
- the polarity of the wiring
- the direction convention adopted
- the calibration procedure
- the calibration coefficients
- the direction of the wheel on the track
- the particular details of a number of spreadsheets used in the analysis of the data
- the particular details of the software used to plot the results

At the time of writing this paper, in the light of the results, all are being painstakingly checked through again, and it is hoped the work will be completed by the time of the conference. Doing so will either confirm the results, pointing to tire scuffing as the reason for the unexpected outcomes, or correcting a sign buried deep within the analysis.

Experience with Past Testing at CAPTIF

The unusual longitudinal and transverse values were not unexpected: the CAPTIF test rig was originally equipped with a slip ring device between the inner and outer wheels on the dual tire to allow the tires to turn at different speeds. Eventually it was removed as it was not overly practical and it was found that not using it did not appear to effect road test results.

Earlier tests on chip seals showed that the effects of tire scuffing were not noticeable when using single tires to study road texture loss. Tests on sensitive surfaces such as open graded porous asphalts have also suggested that the effect is not noticeable when dual wheels where used to study fatigue in thin pavement surfaces: no unusual fretting of the surface and no fatigue was seen.

Conclusion

An apparatus was constructed, to measure compressive, longitudinal, and transverse loads imposed on strain gauged steel pins by full scale single and dual tires running over them. Wheel loads of 40 and 50 kN, were tested in the CAPTIF full-scale, indoor road testing facility owned by Transit New Zealand. Inflation pressures of 550 and 690 kPa were used in the single tires, and 280, 550, and 690 kPa in the dual tires.

The measured compressive pin load distributions, indicative of compressive contact stresses, were as expected compared to previous experiments. Peak compressive pin loads increased for increased wheel loads inflation pressures. For dual tires at the lowest inflation pressure, compressive pin loads were greater towards the outer inner tire edges. Compressive loads were not shared equally by the two tires.

Measured longitudinal and transverse pin results were unexpected. The unexpected results may be explained by tire scuffing caused as the tires negotiated the circular test track, or there may have been some flaw in the procedures or data. Work is underway now to check through the results again, including apparatus design, calibration and testing procedures, and software, to confirm or correct the results.

Acknowledgements

References

De Beer, M., Fisher, C., and Jooste, F.J. 1997. Determination of pneumatic tyre/pavement interface contact stresses under moving loads with some effects on pavements with thin asphalt surfacing layers. Proceedings of the 8th International Conference on Asphalt Pavements, International Society for Asphalt Pavements, 8-14 August, Seattle, Wash., pp. 179-227.

Douglas, R.A., Woodward, W.D.H., and Woodside, A.R. 2000. Road contact stresses and forces under tires with low inflation pressure. Canadian Journal of Civil Engineering 27:1248-1258.

Golder Associates Ltd. 2007. Report on LTNZ Research Project LTR061, Tyre/road contact stress distributions measured and modelled in three coordinate directions - modelling flexible pavement behaviour using measured contact stresses: a survey of the literature. Report submitted to Land Transport New Zealand, Wellington, New Zealand. Mississauga, Ontario: Golder Associates Ltd. (07-1111-0007) 14 pp.

Lippmann, S.A. 1985. Effects of tire structure and operating conditions on the distribution of stress between the tread and the road. *In* The tire pavement interface, ASTM ASP 929. *Edited by*: M.G. Pottinger and T.J. Yager. American Society for Testing and Materials, Philadelphia, Pa., pp. 91-109.

Marshek, K.M., Chen, H.H., Connell, R.B., and Hudson, R.W. 1986. Experimental determination of pressure distribution of truck tire-pavement contact. Transportation Research Record 1070, Transportation Research Board, National Research Council, Washington, D.C., pp. 9-14.

Seigfried. 1998. The study of contact characteristics between tyre and road surface. D.Phil. thesis, Department of Civil Engineering, School of the Built Environment, University of Ulster at Jordanstown, Jordanstown, Northern Ireland.

Tielking, J.T., and Roberts, F.L. 1987. Tire contact pressure and its effect on pavement strain. ASCE Journal of Transportation Engineering, **113**(1): 56-71.