

TOWARDS THE APPLICATION OF STRESS-IN-MOTION (SIM) RESULTS IN PAVEMENT DESIGN AND INFRASTRUCTURE PROTECTION

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ABSTRACT

Road pavements worldwide are constantly under pressure of ever-increasing demands from economic and other market forces. Because of these forces, road infrastructure needs constant protection and it is therefore necessary to understand the ever-changing operating conditions. Statistics on inter-regional traffic in southern Africa indicate that there is severe overloading of heavy vehicles - up to as much as 70 per cent overloading. The aim of this paper is to highlight the approach and application of the Stress-In-Motion (SIM) technology to assist in an improved definition of the actual tyre/pavement interaction of modern heavy vehicles and their loads on the current road infrastructure. Experience indicates that it is difficult to measure these tyre/pavement interaction forces from real trucks and that the measuring equipment is expensive and difficult to maintain. However, efforts have been made in South Africa to gain an improved quantification of the shape and magnitude of the three-dimensional tyre/pavement forces measured from real trucks. In the paper some SIM data sets collected on two National Highways in South Africa are also briefly discussed. Lastly, this paper provides an initial discussion on potential truck tyre parameters envisaged for Performance Based Standards (PBS) on flexible pavements.

INTRODUCTION

Worldwide, the protection of road infrastructure is a major challenge to road authorities. At the annual meeting of the Transportation Research Board (TRB) in 2003 Deen (2003) stated that:

“...transportation has some special characteristics that have resulted in government’s ownership of most of the fixed infrastructure, while the manufacture, ownership, and operation of vehicles (the big expenses) are left in private hands. Government charges the private sector for the use of its facilities to maximize productivity and deal fairly with users. But determining these charges is complex and is necessarily the product of philosophy as well as sophisticated costing. It is the source of endless squabbling between modes and special interests. This tension, combined with the huge size of the system, the dominance of the private sector, its decentralization, and other factors, makes government intervention into the system on behalf of societal goals often challenging and sometimes unsuccessful”.

The aim of this paper is to demonstrate a technology that may be used to assist both road owners and the private sector towards improving the infrastructure and fostering economic growth. The paper presents the Stress-In-Motion (SIM) technology, which may be regarded as an advanced method of Weigh-In-Motion (WIM). The existing technology of Weigh-In-Motion (WIM) has come a long way in the measurement, definition and classification of vehicles using road systems. The WIM technology has provided good understanding of axle masses, axle group masses, gross vehicle masses, group combination masses etc. using current road networks. However, research and development on WIM is still on-going in both Europe and the USA, especially in the latest Long Term Pavement Performance (LTPP) WIM initiative (FHWA, 2003). The SIM technology assists in the measurement of tyre/pavement contact stresses under moving tyres and is thus referred to as Stress-In-Motion (SIM).

STRESS-IN-MOTION SYSTEM (SIM)- SUMMARY OF SYSTEM DESCRIPTION AND DATA REPRESENTATION

Road-related research in South Africa with SIM systems has been conducted since 1992. Currently a semi-industrial version of this equipment exists for research purposes. This system, referred to as the SIM Mk IV system, is a semi-portable system, but does need installation methodologies as precise as the current commercially available WIM systems.

Typically, the SIM Mk IV system configuration includes single, twin or quad measuring pads, depending on the requirements. For single tyre testing (normally truck tyres), the single pad system is used; the twin system is used for dual truck tyres and the quad system is used for full axle measurements of on-road or test trucks. The current SIM system described here is designed for slow (creep) speed conditions, i.e. < 5 km/hr.

Figures 1, 2 and 3 illustrate the typical SIM Mk IV installation and measurement configurations used in the research and development environment. The single and twin SIM pad configurations during HVS tyre testing are illustrated in Figures 1 and 2. In these cases, the SIM pads were used to measure the contact stresses of the typical slow moving free-rolling tyres that are normally used on the Heavy Vehicle Simulator (HVS).¹

In Figure 3 a typical SIM quad test configuration (full 4-pad) is shown on a typical weighbridge station. This configuration also limits the test speed of on-road vehicles (mostly trucks) to less than 5 km/h. A specially designed test pit constructed of reinforced concrete with an approach and exit slab supports the SIM system indicated here. The SIM measuring system is a time-based system and is triggered by the forward moving tyre using a static acoustic sensor on the side of the road. The axle count and speed per axle are measured using infrared beam triggers. Basic description of the SIM system as well as some data analyses are given by De Beer (1996) and De Beer et al (1997, 1999, 2002).

The tyre-SIM pad interaction is measured in 3D, by an array of sensors across the SIM pad (typically 21 specially designed and calibrated tri-axial load cells at 17 mm centre-to-centre, orthogonal to the direction of the tyre). These load cells measure vertical, lateral and longitudinal loads during one pass of the tyre, typically at an instantaneous sampling frequency of between 150 Hz and 1500 Hz. The Society of Automotive Engineers (SAE) tyre axis sign convention (Gillespie, 1992) used for the SIM testing is illustrated in Figure 4.

In total five directional loadings are measured simultaneously, i.e.:

- +X: Forward (Positive) Longitudinal Force;
- -X: Backward (Negative) Longitudinal Force;
- +Y: Positive Lateral force;
- -Y: Negative Lateral Force; and
- +Z: Positive (downward) Vertical force.

In the data reduction process these measured forces are transformed to average contact stresses. It is assumed that the contact stresses measured in this way are a fair representation of the rather complex tyre-road interface stresses from moving pneumatic tyres on a typical dry asphalt surfaced road with average friction properties, and could be used effectively for the purposes of improved road design and evaluation (Roque et al, 2000, De Beer et al, 1997, 1999, 2002).

Calibration issues of the SIM system

Each instrumented pin (tri-axial load cell) of the SIM device is calibrated in the five directions using a miniature high precision load cell in the laboratory. Cross-coupling terms between the loading directions are removed by matrix manipulation and these terms are normally less than a tenth of the terms in the loading direction. The calibration data for each pin is written on an electronic erasable programmable read only memory (EEPROM) in the pin connector. The calibration of the pins is such that a reading of 2.5 volts represents a full-scale load output of 500 Newton in the vertical direction, and of 300 Newton in both the

¹ The HVS systems are normally used to perform accelerated testing and evaluation of both flexible and rigid road pavement systems (ATC, 1985; APT, 1999).

lateral and longitudinal directions. For pin health, pin offsets (i.e. pin output with zero loading) in the three main directions are regularly monitored and any pin showing unacceptable changes in these recorded offsets over time is replaced by a re-calibrated or a new pin. Calibration checks of the system are made before any major test series, and research is continuing to optimise the measuring pin design and calibration processes.

Outputs from the current SIM Mk IV system

The following information can be obtained from a single SIM measurement:

- Axle speed (the speed is measured for each axle of a truck);
- Distance between each axle²;
- Weight (kg) and/or load (kN) transmitted to tyre(s);
- ½ - axle weights and loads;
- Full axle weights and loads;
- Gross Vehicle Mass (GVM) of trucks;
- Gross-Combination Mass (GCM) for trucks and trailers;
- For each tyre: 3D-Vertical (Z) contact stress (or load) profile;
- For each tyre: 3D-Lateral (+/- Y) contact stress (or load) profile;
- For each tyre: 3D-Longitudinal (+/- X) contact stress (or load) profile;
- Tyre contact patch length and width; and
- 2D tyre contact patch.



Figure 1. Single SIM pad configuration (used under Heavy Vehicle Simulator (HVS) with single test tyre).

² In the case of HVS SIM testing, this distance is not measured since there is only one axle.



Figure 2. Twin (or dual) SIM pad configuration (used under Heavy Vehicle Simulator (HVS) with dual test tyres).



Figure 3. Quad (full) SIM pad configuration at a typical weighbridge site on National Road 3 (N3), near Heidelberg in Gauteng.

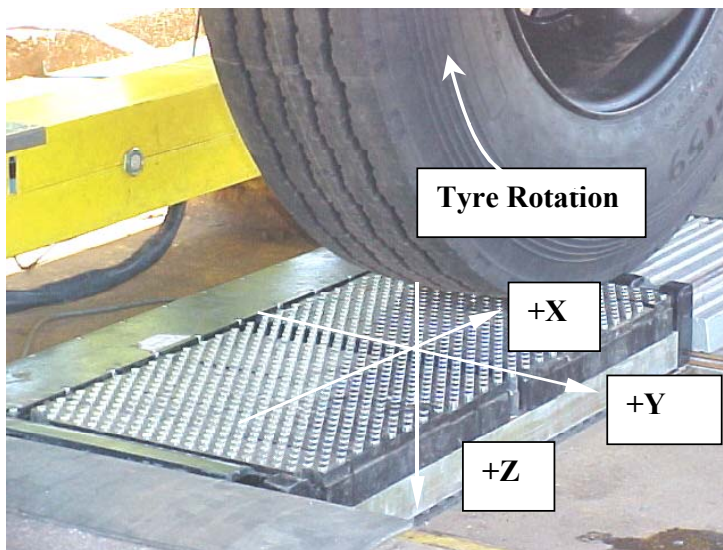


Figure 4. SAE sign convention used during SIM measurements. X-Longitudinal, Y-Lateral and Z vertical loads/stresses.

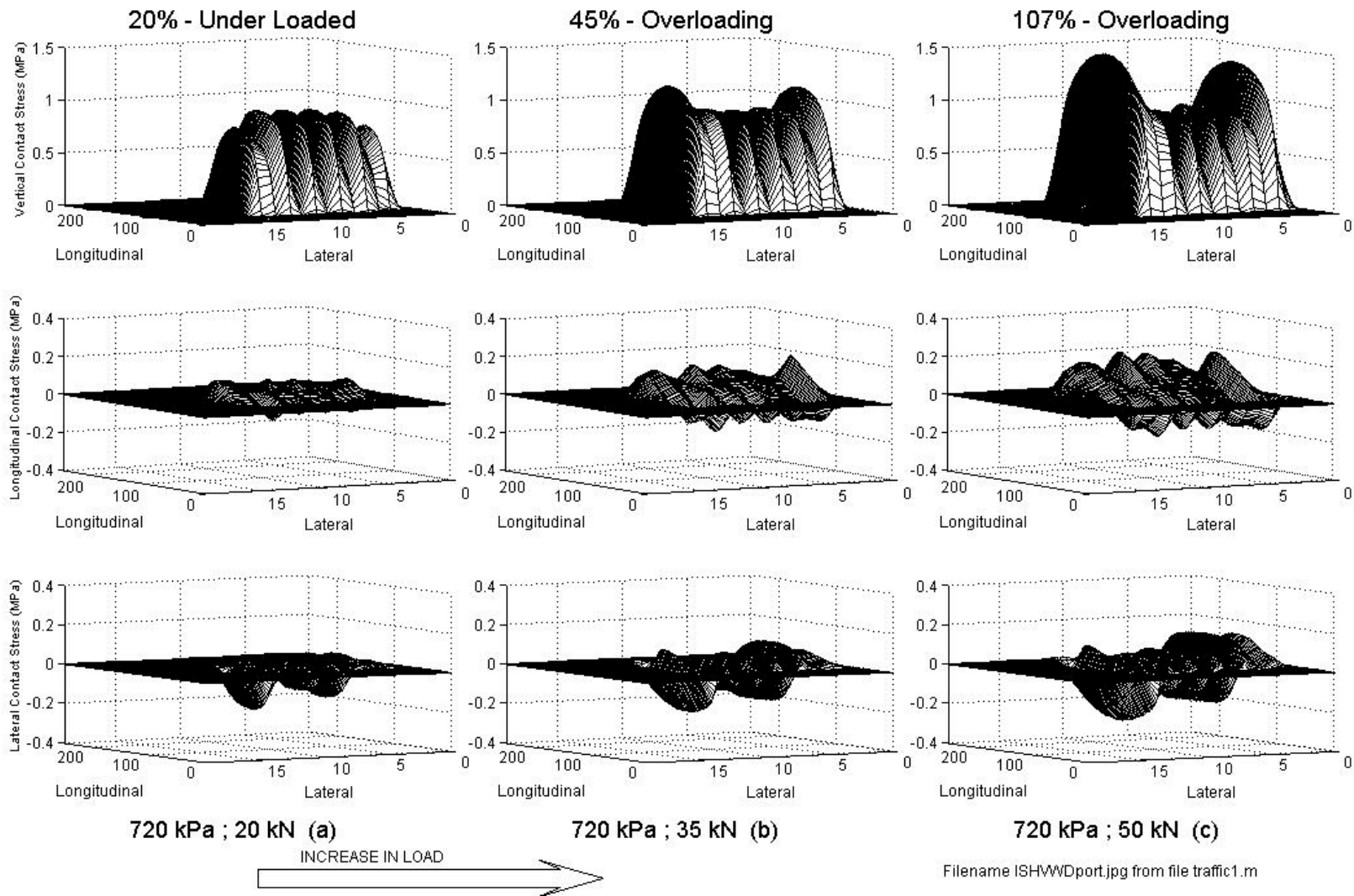
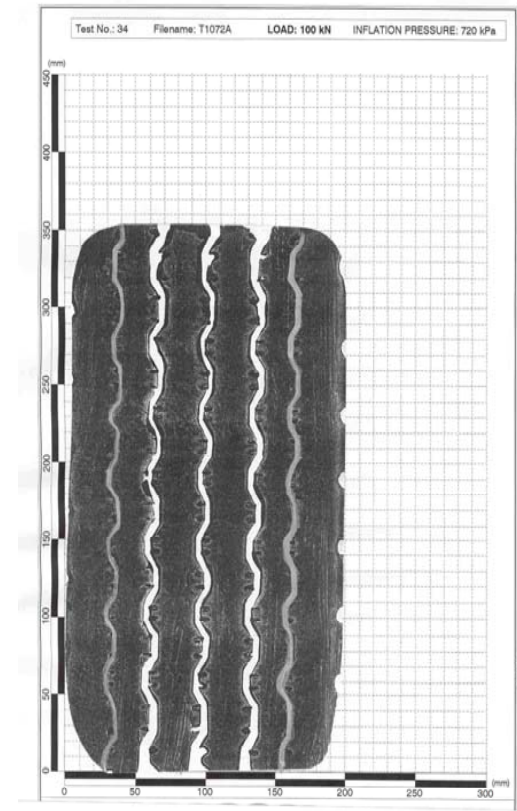
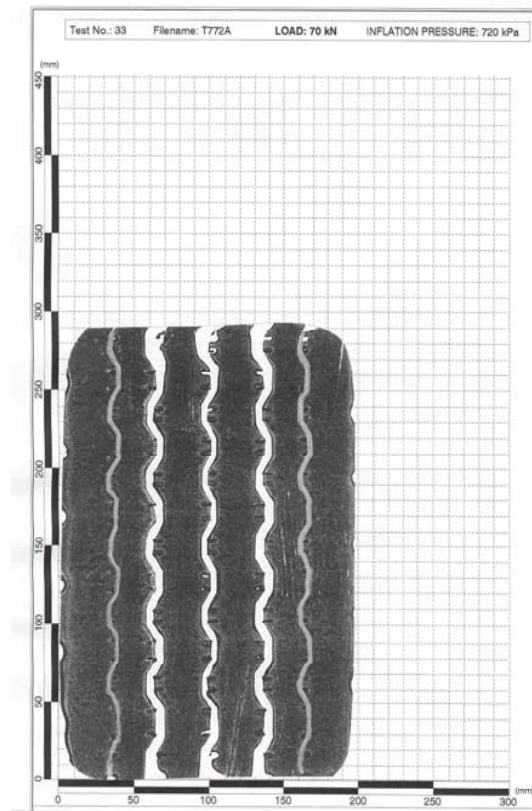
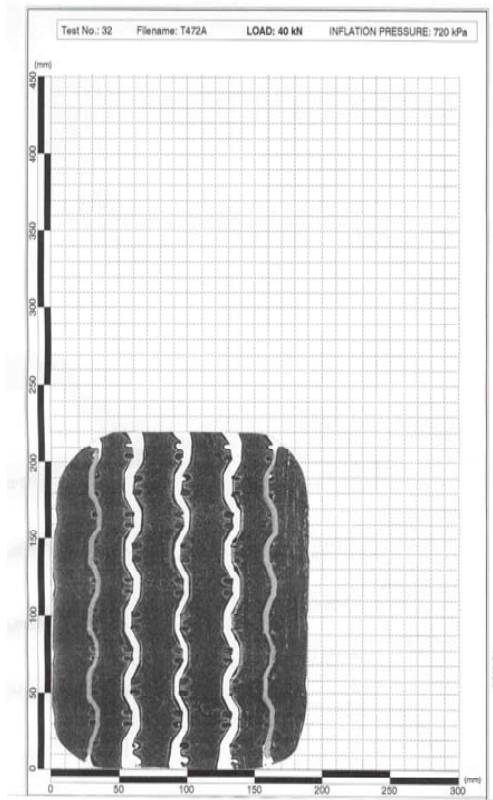


Figure 5. (a) Case 1: 720 kPa, 20 kN (n-shape); (b) Case 2: 720 kPa, 35 kN (m-shape) (c) Case 3: 720 kPa, 50 kN (m-shape).



(a) Tyre Print: Case 1: Single Loads 20 kN, 720 kPa

(b) Tyre Print: Case 2: Single Load 35 kN, 720 kPa,

(c) Tyre Print: Case 1: Single Load 50 kN, 720 kPa

Figure 6. Static tyre prints.

Examples of typical measured SIM data sets

Three data sets (cases) were selected as indicated in Table 1, to illustrate some example data sets from previous SIM measurements. The test tyre was a single standard truck tyre 11R22.5, normally used with HVS Mk III testing in South Africa (De Beer and Fisher, 2000). Case 1 represents an “under-loaded” case for the given tyre inflation pressure and Cases 2 and 3 represent heavy “over-loaded” cases within the context of the HVS research environment. The HVS test tyre was non-driven and free rolling over a single SIM pad at a speed of 0.3 m/s (1.08 km/hr).

Table 1. Example of loading cases presented in this paper (De Beer and Fisher, 2000).

Case	Cold Inflation Pressure (kPa)	Single tyre Loading (kN)	% of rated loading @ 720 kPa ³	Comments
1	720	20	- 20	Under-loaded
2	720	35	+ 45	Overloaded
3	720	50	+ 107	Extremely overloaded

The three cases are graphically illustrated in Figures 5a, 5b and 5c. The figure indicates three test conditions of loading (20 kN, 35 kN and 50 kN) at a constant inflation pressure of 720 kPa. For Case 1 (Figure 5a) the vertical contact stress distribution appears to be relatively uniform concave bulge (referred to as “n-shape”, where peak stresses occur towards the centre across the tyre patch), and is assumed to be representative of acceptable loading conditions for the purposes of pavement design. Cases 2 and 3 (Figures 5b and 5c) represent over-loading and extreme overloading (referred to as “m-shape”, where two distinctive convex like peak stresses occur at the tyre edges) for the given tyre inflation pressure. In both these cases bulging of the tyre walls occurs and it is clear that the tyre load is transferred to the tyre edges and demonstrates why this is an unacceptable loading condition for normal truck and pavement operations. In practice, increasing the tyre inflation pressure sometimes compensates for these cases. Normally these “bulging” conditions result in tyre failure as well as in pavement surfacing failures. It should however be stated that more field results are needed to determine the loading condition on a specific road section. It is also accepted that overload control and good tyre maintenance should be able to guard against the overloading indicated here. In all three cases the measured longitudinal and lateral stresses are also illustrated in Figures 5a, b and c. These figures also illustrate the increase of the horizontal stresses with increased loading. These contact stress measurements compare favourably with those based on computed stresses from a Finite Element tyre model (Zhang et al, 2001).

The static tyre prints of the three cases are illustrated in Figure 6a, b and c. It is clear that only the length of the tyre contact patch increases with increased loading, while the width (w) remains constant. This is typical of most of radial truck tyres now being used. The increase in length was approximately 32 per cent for Case 2, and 62 per cent for Case 3, relative to Case 1. The test tyre consisted of six ribs. (Note that the effect of increased tyre inflation pressure as a direct result of tyre loading and tyre deflection was not studied here, but it is accepted that the inflation pressure increases with increased loading owing to a reduction in the volume of the tyre.)

The absolute values of maximum X, Y, and Z stresses for the three cases are summarized in Table 2, as well as the stress ratios⁴ and increases in stress relative to Case 1.

It is clear from the cases studies here that all the maximum stresses increased with increased loading, with the longitudinal stresses (X) showing the greatest increases, followed by the vertical stresses (Z). It is interesting to note that the percentage increase in longitudinal stresses compares with that obtained from the loading levels.

³ For this test tyre the rated load at 720 kPa = 24 kN

⁴ Stress Ratio = [(Maximum Contact Stress)/(Maximum Vertical Contact Stress)] * 10

Table 2. Maximum stresses and stress ratios*.

Case (shape)	Increase in load over Case 1 (%)	Maximum Vertical Stress: Z (kPa)	Increase over Case 1 (%)	Maximum Lateral Stress: Y (kPa)	Increase over Case 1 (%)	Maximum Longitudinal Stress: X (kPa)	Increase over Case 1 (%)
1 (n-shape)	-	953 (10)	-	191 (2.0)	-	102 (1.1)	-
2 (m-shape)	75	1189 (10)	25	209 (1.8)	9	185 (1.6)	81
3 (m-shape)	150	1486 (10)	56	261 (1.8)	37	210 (1.4)	106

* Stress ratio = [(maximum contact stress)/(maximum vertical contact stress)]* 10

The Normalised Contact Stresses (NCP)⁵ for the three cases are given in Table 3. The NCP is an indication of the maximum measured contact stress exceeding the tyre inflation pressure (De Beer et al, 1997). It is postulated that this parameter could be a valuable tool for pavement analysis and design, as will be demonstrated later in the pavement design example. In general the NCP increases with increased tyre loading.

Table 3. Normalised Contact Stresses (NCP).

Case	Maximum Vertical Stress: Z (kPa)	NCP _Z for Vertical Stress	Maximum Lateral Stress: Y (kPa)	NCP _Y for Lateral Stress	Maximum Longitudinal Stress: X (kPa)	NCP _X for Longitudinal Stress
1	953	1.32	191	0.27	102	0.14
2	1189	1.65	209	0.29	185	0.26
3	1486	2.06	261	0.36	210	0.29

Interface shear stresses

Several studies have indicated that there are various relationships between measured contact stresses and tyre loading and that there is a general increase in contact stresses with increased loading ((Van Vuuren, 1974; Clark, 1981; De Beer et al, 1997; Blab, 1999). These studies have also shown the effect of tyre inflation pressure on measured stresses. Douglas (2001) and Douglas et al (2003) reported interesting phenomena referred to as “contact shear force excursions”. The excursion plots are obtained by plotting the lateral and longitudinal stresses (or loads), as illustrated in Figures 7, 8 and 9 for the three loading cases. In this paper the shear stress excursions are given in stress units. The shear stress excursion can be defined as the in-plane (X-Y) stress regime as defined by an individual measuring pin of the measuring system, such as the SIM. A single measuring pin therefore represents a single point of contact with the rubber.

It is clear from Figures 7, 8 and 9 that there is a general increase in shear stress excursions with increased loading across the tyre patch. For illustration purposes the figures indicate the results of only four positions across the tyre patch, i.e. position 3, 5, 9 and 12. (in the case of the SIM there are a total of 12 measuring pins in contact with the tyre tested here). Pin 3 represents a condition in the middle portion of the edge rib, Pin 5 on the edge of a tread groove, Pin 9 in the middle of one of the tyre centre ribs, and Pin 12 on the inside edge of the outside rib. In all three cases discussed here, it is clear that Pin 12 undergoes the highest horizontal stress regime under the rolling action of the tyre, starting at zero stress (before tyre contact), then underwent a negative stress in both the x and y directions, after which there is a stress reversal back to zero again. Similar patterns were observed for the other pins. It is also clear that the sign of the stresses in the lateral direction (i.e. across tyre patch) is a function of the position of the measuring pin relative to the tyre patch and therefore also the tyre tread pattern. The shear stress excursion results (Figures 7, 8 and 9) showed that the lateral and longitudinal stresses could be as high as 250 MPa and 165 MPa, respectively. The shear stress excursion can be visualised as a type of “screwing” action between tyre and measuring pin, and was first reported by Siegfried (1998). With the measuring pin deflection known under known loading

⁵ Normalised Contact Stress (NCP) = (maximum contact stress)/(inflation pressure)

conditions, Douglas et al (2003) extended this concept into “interface energy”, which has proved to be a very promising parameter in the study of asphaltic binders for chip-seal road surfaces.

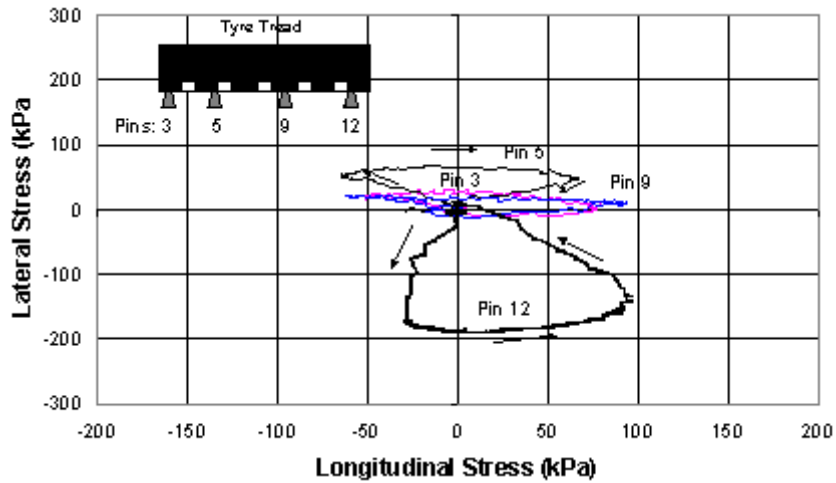


Figure 7. Horizontal shear stress excursion for four sensors: Tyre 20 kN, 720 kPa.

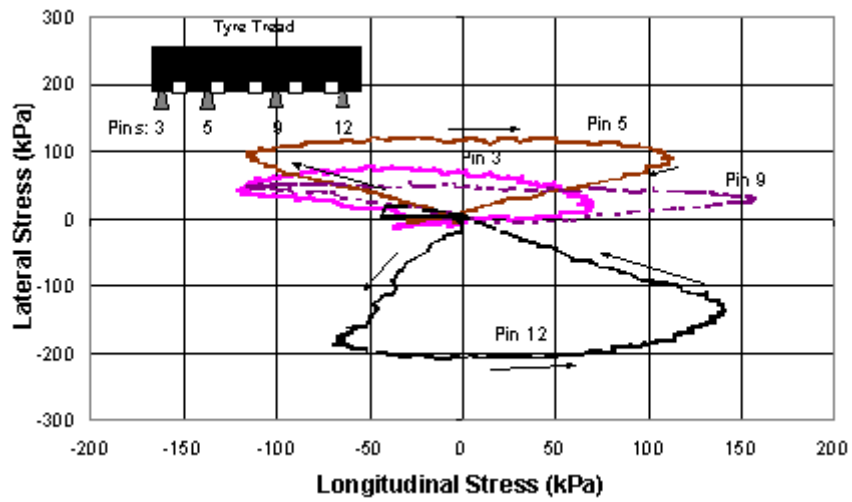


Figure 8. Horizontal shear stress excursion for four sensors: Tyre 35 kN, 720 kPa.

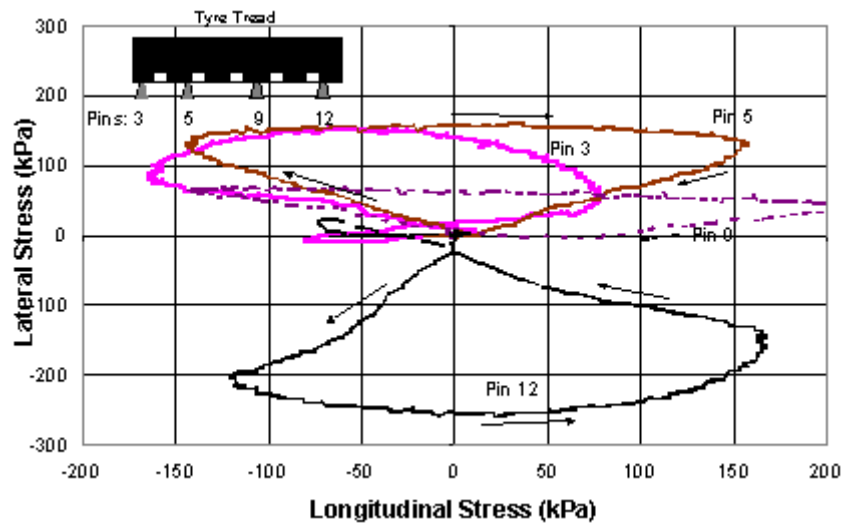


Figure 9. Horizontal shear stress excursion for four sensors: Tyre 50 kN, 720 kPa.

If it is assumed that the measured contact stresses are a good approximation of tyre/pavement interaction, then these stress regimes (or excursions) might be a good indicator of the working stress conditions of individual aggregates (or groups of aggregates) under the action of a rolling pneumatic tyre. The information gained by these observations could be very useful in the development of new laboratory test and evaluation methods (or for the adaptation of existing ones) for designing surfacing seals as well as for testing the integrity of bitumen or other binders with aggregates. One example of this could be enhancement of the current “Pull-out” test used for surfacing aggregates in South Africa (TG1, 2001), and/or compare “excursion energies” obtained with those typically obtained from the Vialit test for surfacing aggregates, as reported by Douglas et al (2003).

Effect of speed on tyre-pavement contact stress

Very limited research has been carried out to study the effect of speed on the contact stress distribution. Work by Clark (1982) indicated that the shape of the vertical stress along the tyre length changes to be more asymmetrical, with increased speed. In addition it can be postulated that centrifugal forces increase with increased speed, with the result that the diameter of the tyre increases. With a tyre in contact with the road, this increase is restricted by the relatively rigid pavement surface (compared to the flexible tyre), resulting in vertical axle lift. The net result of this axle lift is a reduction in contact area (in the order of 6 per cent reduction at a speed of 100km/hr) for the same loading conditions (Petzer, 1996). This could potentially result in higher vertical contact stresses. Also dynamic effects could become more important at higher speeds, tyre harmonics may also start to dominate the characteristics of the 3D tyre-pavement contact stress distribution. Further, the effect of dynamics on the measuring equipment is also not known currently, and need to be quantified with further studies.

Seitz and Hußmann, (1971) indicated that the contact stress distribution is influenced by factors such as the operating parameters of tyres (type of tyre, longitudinal, lateral and torsional stiffness, internal friction in rubber and cord, tread pattern, type of rubber, friction characteristics of the tread, inflation pressure, tyre dimensions, etc), and the environmental parameters (free-rolling, braking, acceleration, cornering, velocity, driving forces, tyre loading, contact area, weather conditions, tyre slip and temperature effects, as well as friction between tyre tread and pavement). Much more research is needed to quantify the effects of these parameters on modern day truck tyres at higher highway speeds.

It should however further be noted that the effects of vehicle speed will also influence the response of the pavement, such as elastic response parameters, as well as permanent (or plastic) response parameters such as rutting. It is well known that on a relatively smooth pavement the effective magnitude of most elastic response parameters (deflection, strain) decrease with an increase in the speed of pavement loading (See Cebon, 1999; Siddharthan et al (2000); Zafir et al (1994) and De Beer, 1991, 1992)).

Pavement response and top-down cracking

Jacobs (1995), Myers et al, (1999, 2001) Groenendijk (1998) and Weissman and Sackman (1997a, b), amongst others, tried to quantify some of the effects of a 3D non-uniform tyre-pavement contact stress distribution on the surface of the pavement. Most of these researches found tensile and compressive stresses and strains on or near the surface of the pavement close to the loading, depending on the nature of the applied contact stress regime. The majority of results show tensile strains in the region of the edges of the tyre, which could be interpreted as conditions that may contribute to traffic-induced top-down cracking in asphalt pavements.

Linear Elastic (LE) mechanistic analysis on thinly surfaced pavements does indicate maximum damage potential in these regions close to the surface of the asphalt layer, using the SIM data as the applied static pavement loading (see De Beer et al, 1997, 1999, 2002). However, there is no study known to the author, where it was proven beyond doubt that non-uniform 3D tyre-pavement contact stresses are solely responsible for top-down cracking in asphalt pavements. Evidence also exists to show that the construction methodology could contribute largely to top-down longitudinal cracking in thicker asphalt base pavements. In this case weakness in the asphalt is simply because of construction joints, and or segregation of materials during construction. This weakness could contribute to more aggressive cracking by factors such as asphalt shrinking, as well as traffic-load induced cracking from non-uniform contact stresses. (see comments by D L Lippert in Myers et al, 2001). It is therefore suggested that special studies to be carried out to quantify the

relative effect of traffic-induced stresses on the formation or acceleration of construction (or environmentally) related longitudinal top-down cracking in asphalt pavement layers.

MODELLING OF NON-UNIFORM VERTICAL CONTACT STRESSES USING “SIMPLISTIC” MULTI-LAYER LINEAR ELASTIC THEORY (MLLE)

In traditional pavement design and analysis models circular discs of uniform contact stress normally represent the tyre loading. However, more advanced methods exist to model the non-uniform contact stress such as the Finite Element Method (FEM). Several examples exist which demonstrate this capability (Weissman and Sackman, 1997; De Beer et al, 1999, 2002; Blab, 1999; Blab and Harvey, 2000; Long, 2001; Novak et al, 2002; Soon et al, 2002; Collop et al, 2003) but FEM is still not yet used in everyday pavement design and analysis. Therefore it is suggested that a modified approach using multi-layer linear elastic (MLLE) methodology be used. Based upon SIM measurements in the USA, Blab (1999) suggested using regression analysis to obtain the relevant vertical stress for use in MLLE. It was further suggested that three circular loads be used to simulate tyre centre stress (q_c) and tyre edge stresses (q_e). A load distribution factor α can be calculated to estimate both tyre centre loading (F_c) and tyre edge loading (F_e). To simulate the actual tyre imprint, the centre load circle should be situated in the centre axis of the tyre load patch, and the two edge load circles at a distance $d = 0.4w$ of the constant tyre width (w) of the tyre tread (Blab, 1999). See Figure 10.

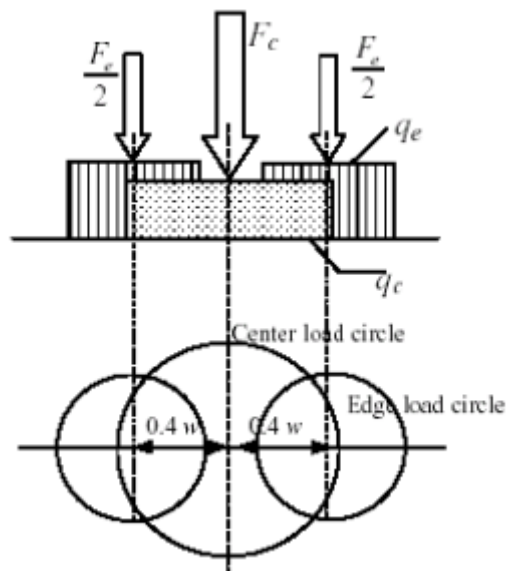


Figure 10. Load configuration to simulate tyre edge and centre load with uniformly distributed loads of circular shape (after Blab, 1999).

In this paper Blab’s approach (Blab, 1999) was used to model a 3-layer thinly surfaced granular pavement to demonstrate the methodology, and the effect of a) single circular loading and b) three circular loadings, using a load distribution factor, α (See Appendix A for definitions). The MLLE methodology used here is limited to vertical load only, and the three cases in Figure 5a, b and c were used for the MLLE analysis. The pavement and loading conditions used for the MLLE analysis are summarised in Tables 4 and 5.

Table 4. Summary of pavement conditions for MLLE analysis.

Layer	Thickness (mm)	Elastic Moduli (MPa)	Poisson’s Ratio
Asphalt Surfacing (AC)*	20	3500	0.44
Granular Base (G3)**	150	230	0.35
Soil Subgrade	Semi-∞	100	0.35

* AC = Continuously graded thin asphalt surfacing (from Theyse and Muthen, 2000).

** G3 = Graded Crushed Stone, 98 % to 100 % Mod AASHTO, Plasticity Index (PI) < 6 (from Theyse and Muthen, 2000).

Table 5. Summary of vertical pavement loading conditions for MLLE analysis.

Case	Load (kN) (F)	Contact Stress, q (MPa)	Load Radii, r (mm)	Load distribution factor: α (See Appendix A)	X, Y Position of load circles ($w = 203$ mm) (mm)
Case 1-std*	20	720	94	n.a	0,0
Case 1	$F_c=11.14,$ $F_e/2=4.43$	$q_c= 523,$ $q_e= 367$	$r_c= 82$ $r_e= 62$	1.26	-81,2 0,0 +81,2
Case 2-std*	35	720	124	n.a.	0,0
Case 2	$F_c=17.98,$ $F_e/2=8.51$	$q_c= 536,$ $q_e= 583$	$r_c= 103$ $r_e= 68$	1.06	-81,2 0,0 +81,2
Case 3-std*	50	720	149	n.a.	0,0
Case 3	$F_c=23.05,$ $F_e/2=13.47$	$q_c= 549,$ $q_e= 760$	$r_c= 116$ $r_e= 75$	0.86	-81,2 0,0 +81,2

* std = Standard single circular loading with uniform pressure.

The MLLE analysis discussed here was performed using the South African Mechanistic Pavement Design and Analysis methodology, using mePADS software as discussed by Theyse and Muthen, 2000.

The loadings F_c and F_e were calculated using the regression coefficients from Blab (1999), together with the associated load distribution factor α . The results in Table 5 indicate that for Cases 1, 2 and 3 the values obtained for the loading (and hence the contact stresses) in the tyre centre differed from the loading at the tyre edges, especially for Case 3, the extremely overloaded case.

Results and discussion

The following pavement response results were analysed in the pavement at the bottom of the asphalt surfacing, in the granular layer and at the top of the subgrade layer (see Figures 11 to 14):

- Applied vertical stress;
- Vertical elastic deflection on surface;
- Horizontal tensile strain at bottom of asphalt surfacing;
- Vertical elastic strain on top of the subgrade; and
- Estimated pavement layer life estimated based on Theyse and Muthen (2000).

Applied vertical stress

Figure 11 represents the tyre load intensity (i.e. contact stress) and it is clear that the modelling procedure suggested by Blab (1999) does differentiate between tyre centre loading vs. tyre edge loading. For the standard (std) cases, where the tyre loading is represented with a single circular disc with uniform pressure, the contact stresses at the tyre centre and the tyre edges are very similar. However, according the methodology suggested by Blab (1999) (Figure 10) the stresses at the tyre centre differ from that at the tyre edges. For Case 1 the edge stresses are lower than the stresses at the tyre centre, but for Cases 2 and 3 these stresses exceed those at the tyre centre. According to this analysis, the resultant tyre centre contact stress for both Cases 2 and 3 are somewhat lower than those in the standard cases, whilst the resultant contact stresses at the tyre edges are almost double those of the standard cases. This is also true when the tyre edge stresses are compared with those stresses at the tyre centre. See Figure 11.

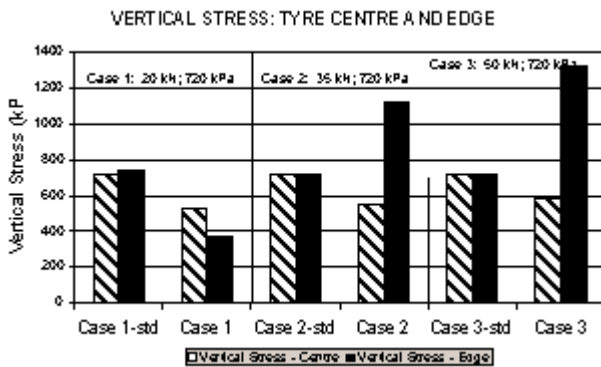


Figure 11. Vertical stress @ z = 0 mm.

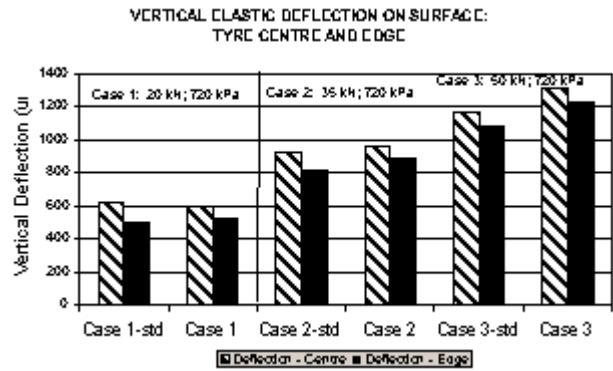


Figure 12. Vertical elastic deflection @ z = 0 mm.

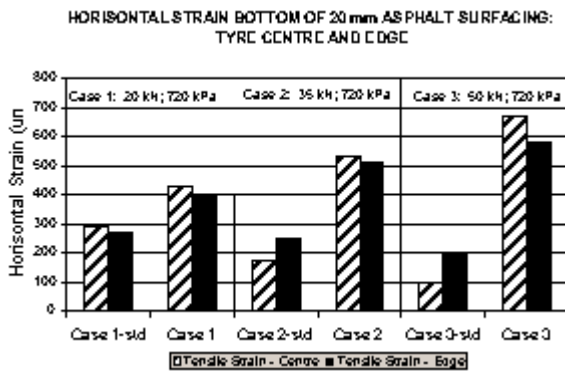


Figure 13. Horizontal tensile strain @ z = 20 mm.

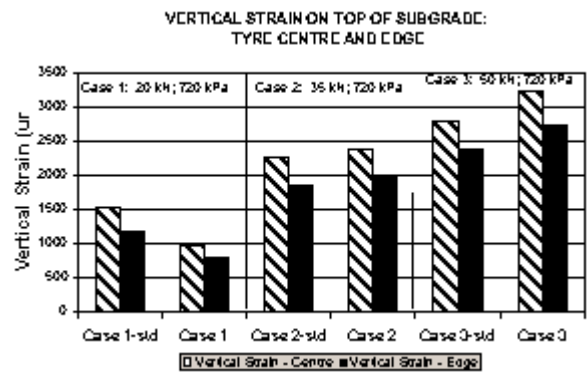


Figure 14. Vertical elastic strain on subgrade @ z = 170 mm.

Vertical elastic deflection on surface

The vertical elastic deflection on the surface of the pavement ($z = 0$) is illustrated in Figure 12. According to the analysis the vertical surface deflections do not reflect the higher tyre edge loading in these cases. Very similar (in fact slightly lower) deflections were obtained between centre and tyre edge positions for all cases studied. The reason for this is that most of the surface deflection in MLE analysis originates from the subgrade. For the load cases studied here it can be concluded that non-uniform contact stresses do not have a significant influence on the elastic deflection on the surface of the pavement studied.

Horizontal tensile strain at bottom of asphalt surfacing

The horizontal tensile strains at the bottom of the asphalt surfacing layer are illustrated in Figure 13. The results indicate that for the standard loading cases the horizontal tensile strain is lower than approximately $300 \mu\text{m}$. It is also interesting to note that the strains decrease with increased loading owing to the development of more compressive states of stress under the tyre at higher loadings modelled with MLE. However, for Cases 2 and 3 the tensile strains increased remarkably both at the centre and edges of the tyre, with the calculated horizontal tensile strain levels exceeding $500 \mu\text{m}$ throughout. This is considered to be a modelling characteristic, and might potentially be used to study the effect of tyre edge loading, using the 3-circle approach illustrated in Figure 10. For the cases studied here it is concluded that the horizontal tensile strain modelled in this way is greatly influenced by the method of representation of the load (or contact stress).

Vertical elastic strain on top of the subgrade

The vertical elastic strain on the top of the subgrade is illustrated in Figure 14. Again, as for the vertical deflection (which is computed from the vertical strain) there are only relatively small differences between the results of the different modelling approaches used here. It is therefore concluded that it is unlikely that overloaded tyres with tyre edge stresses exceeding the tyre centre stresses will have an effect on the vertical strain at subgrade levels for the type of pavement studied here.

Pavement layer life estimates

Using the mePADS approach (Theyse and Muthen, 2000) the “lives” of the different layers in the modelled pavement under the different single tyre loading conditions were estimated at (X, Y) positions- i.e. (0, 0) and (81.2, 0) at z-depths of 0 mm (surface), 20 mm (bottom of asphalt layer) and 170 mm (top of subgrade). The results are illustrated in Figure 15.

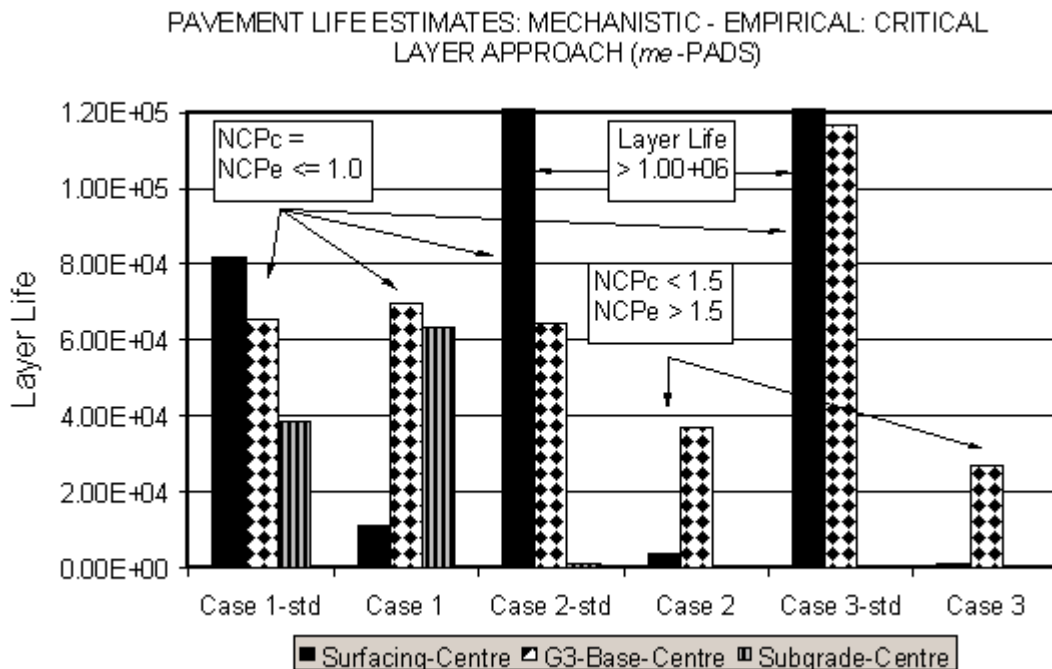


Figure 15. Estimations of layer “life” based on the me-PADS analysis in the centre position of the tyre.

The figure indicates that for the standard (analytical) cases of tyre loading represented by a single circular footprint with uniform stress, the layer lives for the surfacing and granular base are relatively high. For Cases 2-std and 3-std virtually no life was obtained for the subgrade owing to the very high loading levels applied to the pavement. From comparison of the results of the standard loading with those in which the load was represented by three circular discs (see Figure 10), it is clear that marked changes (mostly reductions) in the life estimations for all layers of the pavement (Cases 2 and 3) occurred. The life of the surfacing was reduced because of the increased horizontal tensile strains as indicated in Figure 13. For Cases 2 and 3, the reduction in the life of the granular layer occurred because of increased shear potential in that layer. For the subgrade the layer life was reduced simply because of increased tyre loading, which increased the vertical elastic strain on this layer. For Case 1 the lives of both the base layer and subgrade layer increased by comparison with the standard case, which is a direct result of the tyre edge stress applied to the pavement being lower than that at the tyre centre.

Performance based standards (PBS)

Performance Base Standards (PBS) for tyres were discussed during a PBS-2003 seminar (PBS, 2003) in Australia. During this seminar it was concluded that more research was required before an adequate performance level for tyre contact stress distribution could be established. What is of interest here (see Figure 11) is that for the standard loading cases modelled (i.e. “n-shape” distribution), the normalised contact stresses (NCPs) were in the order of unity (~ 1) both at the centre of the tyre (NCP_c), and at the tyre edges (NCP_e), whilst for the other cases (i.e. overloaded at constant inflation pressure, i.e. “m-shape” distribution) the NCPs exceeded this value of 1.0. The NCP at the tyre centre was $1.0 < NCP_c < 1.5$, and for the NCP at the tyre edge, $NCP_e > 1.5$. (The actual measured NCPs for the three loading cases studied here are given in Table 3, which clearly indicates that the greater the total tyre loading (at constant inflation pressure) the higher the tyre edge stresses and, hence, the higher the associated NCPs.) Since the “m-shape” distribution is characterized by two distinctive peak stresses (at both the tyre edges), multiplication of the NCP by a shape

factor of 2 might be considered. Obviously then the shape factor for the “n-shape” equals unity, since only one distinctive peak stress occurs in these cases.

Based on the rather elementary analysis presented here, it is hypothesized that tyre-loading conditions exhibiting NCPs > 1.0 could be especially detrimental to thinly surfaced flexible pavements. A more detailed analysis is, however, needed to establish more appropriate conditions (or limits) for the associated NCP conditions, but it is the authors’ opinion that the concept of NCP could form a potential basis for the required performance measure of tyre contact stress distributions for flexible pavements.

Based on the foregoing, the performance level could initially be set at $NCP \leq 1.5$, say, for thinly surfaced granular pavements, representing a distinct “over-pressure” relative to the inflation pressure.

It is further hypothesized that a similar PBS concept could be used for the horizontal stresses (or loads) applied to pavements in low-speed turns and at constant speed on uphill grades by the tyres of multi-axle groups. However, this aspect was not studied here, but some work on free rolling tyres has been done to investigate the contribution of the horizontal stresses on thinly surfaced flexible pavements (De Beer et al, 2002).

CONCLUSIONS AND RECOMMENDATIONS

In this paper the use of Stress-In-Motion (SIM) technology is demonstrated, which could be used to gain information to further the understanding of the rather complex tyre/pavement interaction. This information could be utilized to improve current pavement design and analysis models, and also improve the understanding of the effects of overloading on thinly surfaced flexible pavements. Examples of tyre loading at constant inflation pressures indicated the presence of relatively high edge stresses at the very high loading levels (referred to as “m-shape” distributions), by comparison with the lower load levels (referred to as “n-shape” distributions). For the examples discussed in this paper, maximum vertical contact stresses seems to be as much as twice the inflation pressure (at extremely high levels of loading). For normal loading conditions the maximum vertical stress exceeds the inflation pressure by approximately 30 per cent. Results also show that the length of the tyre contact patch increases with increased loading, while the width of the tyre width remains constant.

It was also demonstrated that the quantification of the horizontal interface shear forces (or stresses) between the tyre and the surface of the road could assist in the understanding of the horizontal stress regime in the tyre patch of a moving tyre on a coarse surface. Stress excursion results discussed in this paper showed that the lateral and longitudinal stresses could be as high as 250 MPa and 165 MPa, respectively. This information could potentially be used to improved current laboratory test methodologies for chip and spray surfacing seals.

It was further demonstrated that the improved modelling using multiple circles for pavement analysis, instead of a single circular disc to represent the tyre (especially when overloaded) has a marked effect on the estimation of the “life” performance of the pavement. This type of analysis could be useful for quantification of the effect of traffic loading (including overloading) on road infrastructure. Future “simplistic” models should also consider including the effect of increased length of the contact patch. For thinly surfaced pavements with granular bases, it seems that the horizontal tensile strain at the bottom of the asphalt surfacing is the most sensitive to the shape of the applied vertical contact stress (i.e. “n-shape” or “m-shape”, as well as the lateral stresses (See also De Beer et al 1997, 1999)).

The concept of normalised contact stress (NCP) is introduced for the vertical, lateral and longitudinal stresses. It was shown that the higher the NCP the lower the “life” of the pavement, which coincides with the increased contact stresses, applied to the pavement. It is suggested in this paper that the NCP could potentially be used as the performance measure in Performance Based Standards (PBS). More research, however, is necessary to finalise the appropriate performance level of NCPs, for the vertical, lateral and longitudinal directions in the tyre contact patch of a moving tyre.

The following are recommended:

- Continuing research with the SIM technology at higher vehicle speeds, on horizontal curves and up- and downhill traffic;
- Analysis using a wider range of pavement types;
- Analysis of a wider range of tyre types;
- Modelling increased contact patch length as a result of increased loading; and
- Further investigation into a suitable performance measure (such as the normalised contact stress (NCP)) for truck tyre pavement interaction in the context of Performance Bases Standards (PBS).

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APPENDIX A

Load distribution factor from Blab (1999)

In order to take into account the different loading conditions at the tyre edge and the tyre centre for improved load modelling in pavement design when only the total applied vertical tyre load F_z is known, two tyre load distribution factors α_e and α_c are introduced. These distribution factors are defined as the ratio between the vertical tyre edges loads F_e or the vertical tyre centre load F_c , respectively, and the total applied vertical tyre load F_z :

$$\left. \begin{aligned} \hat{\alpha}_e &= \frac{F_e}{F_z} \\ \hat{\alpha}_c &= \frac{F_c}{F_z} \end{aligned} \right\} \text{ where } \hat{\alpha}_e + \hat{\alpha}_c = 1 \dots\dots\dots \text{Equation A.1}$$

As the sum of factors α_e and α_c must be 1, a simple tyre load distribution factor α can be introduced, which itself is defined as the ratio between the centre and the edge load distribution factor. This load distribution factor α may now be used to calculate α_e and α_c in order to derive both the vertical tyre edge and tyre centre load from the total applied vertical load:

$$\left. \begin{aligned} \hat{\alpha}_e &= \frac{1}{1 + \hat{\alpha}} \\ \hat{\alpha}_c &= 1 - \frac{1}{1 + \hat{\alpha}} \end{aligned} \right\} \text{ where } \hat{\alpha} = \frac{\hat{\alpha}_c}{\hat{\alpha}_e} \dots\dots\dots \text{Equation A.2}$$

Where in Equation A.1 and A.2:

- α_e = tyre edge load ratio; F_z = applied vertical tyre load [kN].
- α_c = tyre center load ratio; F_c = vertical tyre center load [kN].
- α = tyre load distribution factor; F_e = vertical tyre edge load [kN].

Accordingly, the tyre load distribution factor α defined above was determined for all SIM measurements performed with the three types of tyres tested in this study. By means of regression analysis, the influence of the tyre inflation pressure p_i and the applied vertical tyre load F_z on the factor α was investigated.

Blab (1999) developed a bivariant function in order to calculate α based on regression analysis.

Accordingly, the tyre load distribution factor α defined above was determined for all SIM measurements performed with the three tyre types tested in this study. By means of regression analysis, the influence of the tyre inflation pressure p_i and the applied vertical tyre load F_z on the factor α was investigated. From all different regression functions tested, again a simple bivariant linear function shows the best fit. The fit seems sufficiently good to be used to estimate the load distribution factor α by facilitating the following equation:

$$\alpha = k_1 + k_2 p_i + k_3 F_z \dots\dots\dots \text{Equation A.3}$$

For this study the following regression values for α from Blab (1999) were used:

$$k_1 = 0.840, k_2 = 9.493 \cdot 10^{-4} \text{ and } k_3 = -1.336 \cdot 10^{-2}$$