TOWARDS IMPROVED MECHANISTIC DESIGN OF THIN ASPHALT LAYER SURFACINGS BASED ON ACTUAL TYRE/PAVEMENT CONTACT STRESS - IN - MOTION (SIM) DATA IN SOUTH AFRICA

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Abstract

The purpose of this paper is to provide information on actual tyre/pavement contact stresses, which seem to be not only non-uniform, but have maxima exceeding the current pavement design value of 520 kPa. For measurement of these stresses under slow moving trucks, a system known as the **Vehicle-Road-Surface-Pressure-Transducer-Array (VRSPTA)** was developed. Over the last 20 years the inflation pressure of heavy trucks has increased from an average of 620 kPa to 733 kPa, and the VRSPTA indicates that actual contact stresses are greater than the inflation pressures, depending also on the tyre load. Related to the tyre contact stresses is the degree of overloading found in South Africa. During 1997, approximately 90 000 heavy vehicles were weighed in South Africa, 35 per cent of which were overloaded in terms of the new load legislation. In order to better understand pavement surface distress issues, pavement designers and road authorities should take cognizance of this, and models to be developed should make provision not only for the higher contact stresses, but also for load/stress idealizations other than the traditional circular disk of uniform stress of 520 kPa and 20 kN load.

1 INTRODUCTION AND HISTORICAL DEVELOPMENT

The subject discussed in this paper centres around the issue of actual tyre/pavement contact stresses of moving vehicles and their effects on flexible pavement systems. This is done by discussing the following:

- Background on Stress-In-Motion (SIM) technology;
- Overview of the South African flexible pavement network and associated research needs;
- Implementation of SIM technology and actual measurements, and
- Mechanistic pavement analysis and evaluation issues.

1.1 Background on Stress-In-Motion (SIM) technology

The technology for the measurement of tyre/pavement contact stresses is generically described as **"Stress-In-Motion" (SIM)** in South Africa (De Beer et al, 1997). Increased truck tyre loading and inflation pressures and, hence, the three dimensional contact stresses play a major role in the service life cycle of flexible pavement surfacings. Recent opinions are also that there is little commonality between distresses found on the flexible pavement system in South Africa and material properties considered in pavement design, performance and asphalt mix design. Pavement surfaces appear to fail in terms of rutting and increases in roughness and cracking. One possible cause of the difficulty in explaining these distresses is that the effective contact stresses between the tyre and the road/pavement surface are not known and are not used effectively in design and analysis procedures. The purpose of this paper is to show that actual tyre/pavement contact stresses are not uniform and exceed the current pavement design value of 520 kPa. The effects particularly of the increased (and some times non-uniform) three - dimensional contact stresses between the tyre and the surface of the pavement are not yet known. Most professionals agree that the current design value of 520 kPa for vertical contact stress between the design tyre and the pavement surface used for both new and rehabilitation design of flexible pavements is a *gross underestimation* of the real contact stress(es). Figure 1 indicates that the inflation pressure of heavy trucks in South Africa increased from an average of 620 kPa in 1974 to 733 kPa in 1995 (De Beer, 1995). Basic research with the VRSPTA also indicated that actual contact stresses are greater than inflation pressures, depending both on the inflation pressure and the tyre load. One of the main factors influencing the contact stress is the type of tyre and its associated inflation pressure and load (See De Beer et al, 1997). Currently in southern Africa, more than 80 per cent of new truck tyres are of the radial ply type, the use of which is still increasing in preference to the older bias (cross) ply tyres. The majority of historical local research with the Heavy Vehicle Simulator (HVS) was done with 11 x 20, 14 ply bias (cross) ply tyres. Since 1997/98 11R22.5 radial tyres have been used on the Gautrans HVS with its accelerated pavement testing (APT) program. In addition to an increase in contact stresses, overloading is still a problem that needs to be overcome. During 1997, approximately 90 000 heavy vehicles were weighed in South Africa, 35 per cent of which were overloaded in terms of the new load legislation (Sallie and Nordengen, 1998).

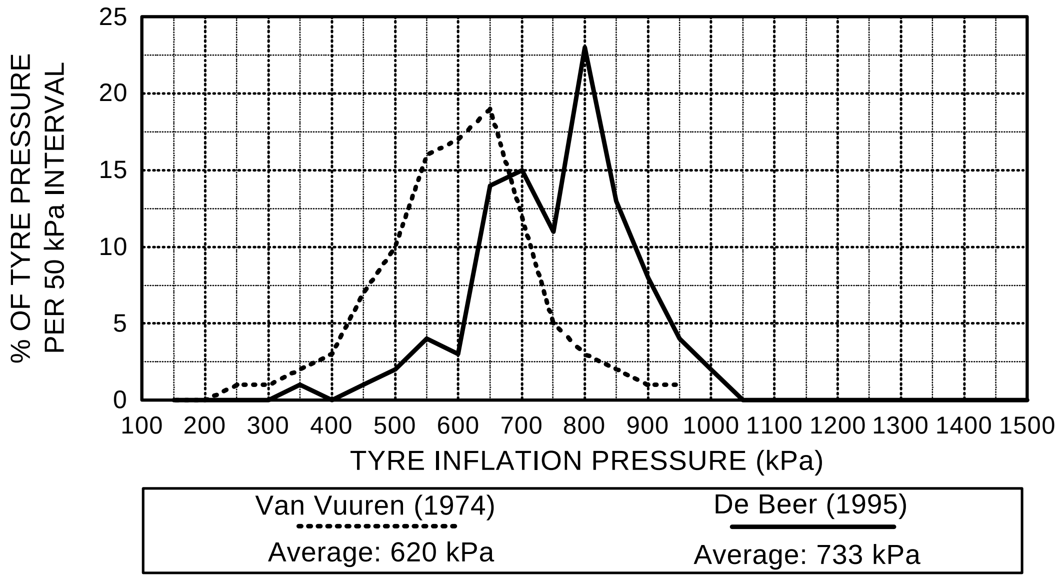


Figure 1
Average measured tyre inflation pressure distributions of heavy vehicles (axle load > 7 000 kg) on roads in the Province of Gauteng, South Africa (1974 to 1995) (De Beer et al, 1997)

Generally, most pavement design models suffer from the lack of more representative contact stress (or load) distributions for both the older type (bias ply) and the new generation of radial pneumatic truck tyres.

The aim of this paper is to provide evidence that the three - dimensional tyre/pavement contact stresses of pneumatic tyres of slow moving vehicles can be measured with relatively good accuracy and are *different* from the general assumptions made for pavement design purposes. Since 1992, the CSIR has been involved with the development of technology to measure the stresses under slow moving trucks and a system referred to as the **Vehicle-Road-Surface-Pressure-Transducer-Array (VRSPTA)** was successfully developed. So far, three measuring devices (VRSPTAs) have been developed of which the first two were used primarily in the research environment where the basic elements of the tyre/pavement interaction problem were studied in detail. In 1992, the first prototype VRSPTA Mark I was developed in association with the Centre for Structural Mechanics of the Laboratory for Advanced Engineering (Pty) Ltd. (LAE) at the University of Pretoria (Raath and Immelman, 1992; De Beer, 1994).

Initial indications from the VRSPTA Mark I were that the tyre/pavement contact stresses could be measured successfully in three dimensions (i.e. vertical, lateral and longitudinal). From this research it was therefore possible to define and quantify three main contact stresses, given below in descending order of magnitude, viz:

- **Vertical Contact Stress:** Positive in the +Z direction, σ_{zz}**;**
- **Transverse (or Lateral) Contact Stress**: *Positive* in the Y direction, τ_{zy},

orthogonal to the direction of the moving wheel (across the contact area), and

- **Longitudinal Contact Stress:** *Positive* in the X direction, τ_{zx}, in the direction of the moving contact area.

On average, for free rolling, slow moving, bias (cross) ply truck tyres, the ratio between the maximum of the three main stress directions, i.e. Vertical: Lateral: Longitudinal is roughly 10:3:1. It was also clear from the research measurements that the distribution of these stresses is not always uniform, but could be very non-uniform. Further, it was demonstrated that the actual contact peak stresses could exceed the tyre inflation pressure by a factor of two to three. For vertical contact stresses it was demonstrated that for relatively overloaded/under - inflated tyres the maximum stresses occur near the tyre sidewalls and not in the tyre centre (De Beer et al, 1994, 1996, 1997; and De Beer and Fisher, 1997). Examples of these measured stresses are given in Figure 2A to Figure 2F. Recently work by Roque et al (1998) also indicated results, similar to those obtained from the VRSPTA in South Africa.

In addition, the earlier work also suggested that for relatively overloaded/under - inflated tyres, the maximum vertical stresses could occur at the tyre edges, and were sometimes more than 2 to 3 times the inflation pressure for bias (cross) ply tyres. See Figures 2A to 2F for basic results from the VRSPTA Mark I. Since the initial research, two further VRSPTA systems were developed in-house by the CSIR. VRSPTA Mark II was the first fully calibrated system using a single unit load cell, mainly for use under equipment such as the HVS. It can also be used under normal vehicles or trucks (Petzer, 1996; De Beer et al, 1996, 1997, De Beer and Fisher, 1997). After considerable success with the VRSPTA Mark II, it was decided to develop a four-unit VRSPTA system for the simultaneous measurement of all tyres and axles of a normal heavy vehicle on the move at slow speed (approximately 5 km/h). This system, referred to as VRSPTA Mark III, was developed during 1996/1998 as part of a demonstration project for the South African National Road Agency Ltd. (SANRA).

2 OVERVIEW OF THE SOUTH AFRICAN PAVEMENT NETWORK

In South Africa, the use of relatively thin (< 50 mm) flexible asphaltic concrete surfacings is a very popular method of providing a good all-weather surfacing for flexible pavements with granular or lightly cemented bases. Traditionally, however, relatively thick asphaltic concrete base pavements were typically constructed in the wetter regions of the country, such as the eastern part of KwaZulu-Natal. In these cases the typical design includes a 100 to 120 mm continuously graded asphaltic concrete base with a 40 mm semi - gap - graded flexible asphaltic concrete surfacing. It is interesting to note here that, for the past two years or so, the G1- base construction has become more popular in these regions since it proved to be the more economic option, provided that the design and construction are up to the relatively high construction standards required for these pavements. In almost all typical medium to heavy pavement structures the use of one or two 150 mm lightly cemented (i.e. stabilized) subbase layers is compulsory. This is to provide a stable and solid platform for the construction of the various granular, cemented or asphaltic base layers (See also TRH 4, 1996).

Typical pavement types and lengths of the South African pavement network are given in Table 1 and 2.

Table 1: Typical rural pavement types and lengths [km] in South Africa (Data: End of 1997)

	PAVED				**UNPAVED**
	FLEXIBLE PAVEMENTS		**RIGID PAVEMENTS**		**(GRAVEL)**
	NATIONAL	**PROVINCIAL**	**NATIONAL**	**PROVINCIAL**	**PROVINCIAL**
DUAL CARRIAGEWAY	1 485	1259	326	None	None
SINGLE CARRIAGEWAY	4 687	54 451	14	None	298 843
SUBTOTAL*	6 172	55 710	340	None	-
TOTAL*	61 882		340		298 843
SUBTOTAL**	7 657	56 969	666	None	
TOTAL**	64 626		666		298 843
TOTAL NETWORK**	65 292				298 843

* Effective km length
** Equivalent single carriageway km

Table 1 indicates that approximately 17,2 per cent of the total actual road network in South Africa, from provincial level upwards, are paved. Therefore a very large potential for mainly flexible asphaltic surfacings currently exists in the country. Of the paved roads in South Africa, approximately 91 per cent incorporate a relatively thin (<50 mm) flexible asphaltic surfacing or seal coat. 13 per cent of these pavements incorporate asphaltic base layers of thicknesses varying approximately from 80 mm to 120 mm (See Table 2). Based on existing road lengths and base types, it is therefore clear that there is a great need to provide more paved road surfaces. Therefore, more cost - effective road construction, maintenance and rehabilitation may be achieved with improved Hot Mix Asphalt (HMA) design procedures and construction processes in South Africa. It is believed that, amongst others, improved tyre/pavement contact stress models could play a central role in this improved design methodology and also in material testing for HMA pavements.

It is interesting to note also that recent research has indicated that the equivalent cost of typical South African pavements compares very favourably with similar pavements internationally for the same bearing capacity. A superficial analysis indicated that a cost saving of between 50 per cent to 80 per cent of initial costs is possible by using typical South African designs for similar bearing capacity (Rust et al, 1998). The prime reason for this potential saving is most probably the use of high quality granular bases on lightly cemented subbases in the South African pavements (i.e. so-called "inverted" pavement designs). However, there are still many gaps in the South African mechanistic-empirical design method (i.e. SAMDM), which need to be investigated for further improvement of the method, including aspects relating to the practical applicability of the method, for use also in countries other than South Africa.

Currently identified research needs and typical pavement distresses that typically need attention locally, are discussed in the next section.

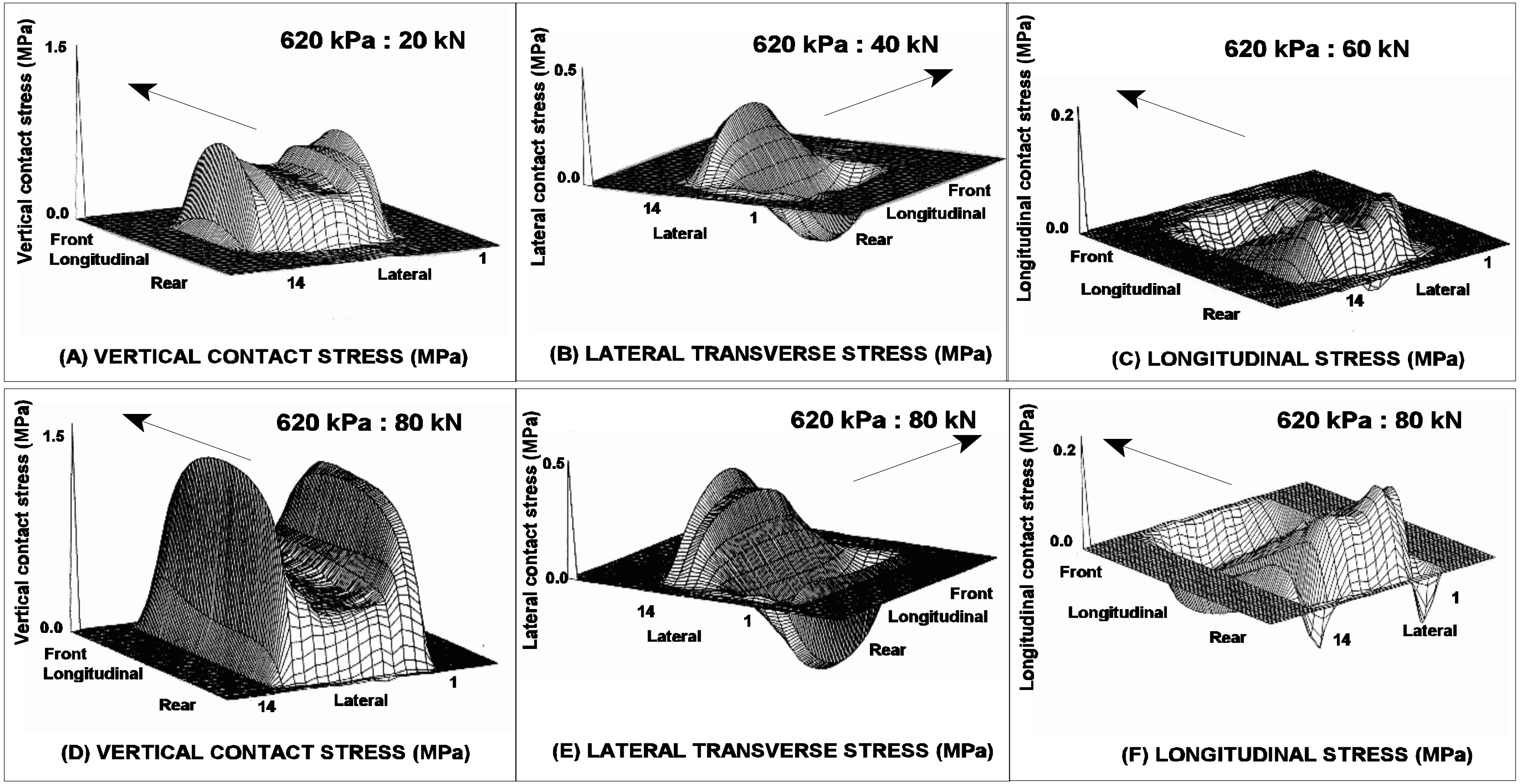


Figure 2: Typical contact stress distributions measured with the VRSPTA system for a slow moving (1,2 km/h) free - rolling smooth single truck tyre (Goodyear 11.00 X 20, 14 Ply rating) . The arrows indicate the direction of the rolling tyre during measurement. (After De Beer et al, 1997)

Table 2: Pavement structure types in South Africa : Breakdown of the type of base and surfacing for National Roads (Data: End of 1997)

Surfacing types for national roads (8 323 km equivalent single carriageway roads in total)			
Chip - and - Spray Seals*	**Hot Mix Asphalt (HMA)**	**JCP (Jointed Concrete Pavement)**	**CRCP****
46,3 %	45,6 %	7,5 %	0,5 %
3 860 km	3 797 km	624 km	42 km

Base and subbase types of the National Road network		
G1/G2 Base on stabilised subbase***	29 %	2 262 km
G1/G2 Base on natural gravel subbase	27 %	2 106 km
Hot Mix Asphalt (HMA)	13 %	1 014 km
Portland Cement Concrete (PCC)	9 %	702 km
C3/C4 Base on natural gravel subbase	7 %	546 km
C3/C4 Base on stabilised subbase	6 %	468 km
G3/G4/G5 Base on natural gravel subbase	6 %	468 km
G3/G4/G5-stabilised subbase	3 %	234 km

* Mostly double seals with stone sizes: 6,7 mm and 13 mm.

** Continuously reinforced concrete pavement - Ben Schoeman dual carriageway between Pretoria and Johannesburg.

*** G1/G2 - material codes according to TRH 14 (1985).

2.1 Current Identified Research Needs on Flexible Pavements in South Africa

In early 1998 a research program was initiated in South Africa on Hot Mix Asphalt (HMA), with the aim of improving existing design procedures for asphalt surfacings on heavily trafficked pavements (HMA Project Management Group (PMG), 1998). In addition, the HMA project includes integration of the new procedures with pavement design, construction and expected performance.

As part of the HMA program, Technical Focus Area number 5 (TFA5) concentrated primarily on design and performance of heavily trafficked flexible pavements (Van Wijk, 1998). The scope of this TFA is to provide inputs to other TFAs on information required for design purposes and to develop processes and procedures for the more effective use of the asphalt mix design results and criteria in pavement and rehabilitation design.

As part of TFA5, typical distresses on South African (SA) pavements were estimated. The typical distresses related to the asphalt surfacing observed on SA pavements are summarised in Table 3. Also indicated are the relative importance and the relationship with pavement design, performance and asphalt mix design.

Table 3: Common types of distresses currently found on flexible pavements in South Africa (adapted from Van Wijk, 1998)

TYPE OF PAVEMENT DISTRESS (MAINLY VISIBLE ON THE SURFACE)	**RANKING:* 1- High occurrence 10-Low occurrence**	**Current incorporation of distress type in:**			
		South African Mechanistic Design Method (SAMDM)		**Performance models (from PMS)**	**Asphalt Mix Design**
		Asphalt Surfacing and base layers	**Subbase and/or subgrade layers**		
Plastic deformation (Rutting)	**1**	×(-only unbound base layers)			(indirect)
Roughness	**2**	×	×		×
Cracks: Fatigue/crocodile	**3**				(indirect)
Bleeding (i.e. "flushing")	**4**	×	na		×
Ravelling	**5**	×	na		×
Stripping/moisture damage	**6**	×	(indirect)	×	
Highly visible asphalt shoving	**7**	×	na	×	×
Permeability too high	**8**	×	(indirect)	×	
Cracks: Block/temperature	**9**	(indirect)	(indirect)		×
Cracks: Transverse/shrinkage	**10**	×	na		×
Cracks: Reflection	**11**	×	na		×

na = not applicable
× = not provided for
= provided for
* These rankings are typically time-dependent and normally follow changes in the design and construction practices, environmental conditions such as moisture and temperature and also traffic loading patterns over time.

The results in Table 3 clearly show that there is little commonality among distresses/properties considered in the pavement design, performance and asphalt mix design. Rutting or plastic deformation of asphalt layers due to both volume change (reduction in constructed voids in the mix) and shape distortion at constant volume are probably the most important properties requiring further investigation, followed by roughness and fatigue cracking. Further shortcomings include the need for improvement of the links between more rational mechanistic pavement design, asphalt mix design and associated performance, as was identified in a recent study by Jooste and Lourens (1998). Here, provision should be made for the mechanistic design of different types of asphalt mixes, such as asphalts with modified binders, etc. The current research needs identified in the TFA5 HMA project are summarised in Table 4.

Table 4: Research needs identified in the HMA project of South Africa (adapted from Van Wijk, 1998)

ITEM	RESEARCH NEED	
Distress types	1	Improved definition of typical distresses found on South African roads.
South African Mechanistic Design Method (SAMDM)	1	Definition and determination of appropriate traffic loading and tyre/pavement contact stresses to serve as inputs to the SAMDM*.
	2	Definition and determination of appropriate material input values for the prediction of traffic - associated cracking and plastic deformation in hot mix asphalt (HMA) layers.
	3	Material inputs and models for the prediction of environmentally associated distresses such as shrinkage cracking in asphalt surfacings.
	4	Relating pavement design properties to asphalt mix design properties.
Performance (more functional than structural)	1	Selection of the most appropriate flexible pavement properties for the prediction of pavement performance.
	2	Guidelines on the establishment of Long Term Pavement Performance (LTPP) sections and databases in South Africa.
	3	Effect of environment on pavement performance (including both “real world” behaviour and Accelerated Pavement Test (APT) behaviour of pavements).

* SAMDM: South African Mechanistic Design Method (De Beer, 1992; Theyse et al, 1996).

This table therefore indicates that more emphasis is to be placed on a dedicated effort in order to better define the asphalt material properties which relate more commonly to the structural and functional behaviour of the asphaltic material as a pavement layer in the pavement system.

2.2 Surface Distresses observed under Accelerated Pavement Testing (APT)

In 1992 a dedicated effort was initiated in South Africa on the improved quantification of tyre/pavement contact stresses. This effort was primarily driven by the results of intensive accelerated pavement testing (APT) studies with Heavy Vehicle Simulator (HVS) that dominated the South African pavement research scene from the mid 1970s to mid 1990s. During this period numerous examples of "surface" related distresses on pavement test sections were noticed. As these pavement test sections were on actual roads, it was recognised that a serious effort was needed to define improved tyre/pavement contact loading and stresses in order to facilitate the mechanistic description and prediction of these distresses. The assumption of a uniform contact stress of 520 kPa for the mechanistic design and analysis procedure just did not seem adequate to describe the observed distresses noted during these years.

Examples of the typical types of distress noted included:

- Surface deterioration, such as micro-cracking, ravelling (or loss of surfacing material);
- Bleeding or "flushing" of surfacing seals - especially the chip - and - spray seals;
- Deformation related to both volume change and shape distortion;
- Deformation resulting from increased moisture in the top untreated (or unbound) layers, or increased temperature on hot mix asphalt (HMA) layers.
- Degradation or "breaking-up" of the surfacings of low volume roads, and
- Traffic associated fatigue cracking of both hot mix asphalt layers and stabilized base layers.

From HVS research an attempt was made to define improved transfer functions for failure criteria used in the current South African Mechanistic Design and Analysis Method (SAMDM) system. This included aspects such as fatigue behaviour of stabilized (or lightly cemented) base and subbase layers, erosion of cemented bases, fatigue of asphalt surfacing and base layers, as well as alternative methods for the plastic deformation of granular pavement layers (De Beer, 1992; Gass et al, 1993; Wolff and De Beer, 1993; Theyse et al, 1996). An abundance of research results from HVS tests in South Africa exists to show that most pavement failures of South African pavements originate from the top downwards, and not from a lack of subgrade support (De Beer et al, 1997). It is also interesting to note that, in a recent detailed study from the Netherlands, it was indicated that non-structural cracking and surface disintegration are the predominant types of distress (65 per cent of pavement area affected) of the Dutch motorway system, consuming also 65 per cent of the total maintenance expenditure (Groenendijk, 1998). More and more professionals therefore agree that pavement distresses from the surface downwards are becoming the predominant mode of loss in serviceability and structural capacity of modern pavement systems. This reinforces the emphasis given in this paper for the improved understanding and quantification needed in the area of tyre/pavement contact stresses.

2.3 Examples of effect of increased vertical tyre contact stresses based on the current SAMDM

In a recent study (De Beer, 1998), a detailed mechanistic evaluation of the effects of increased uniform vertical tyre/pavement contact stresses and axle loads on the catalogue pavement structures of draft TRH 4 (1996) was done, based on the SAMDM. The potential damaging effects of increased vertical contact stresses and axle loads were demonstrated. A typical result of the reduction in calculated layer life as a result of increased contact stress is given in Figure 3. For example, the figure illustrates that there is a reduction of up to approximately 95 per cent in the lives of both the asphalt surfacing and G2 base layer when the uniformly distributed contact stress is increased from 520 kPa to approximately

900 kPa.

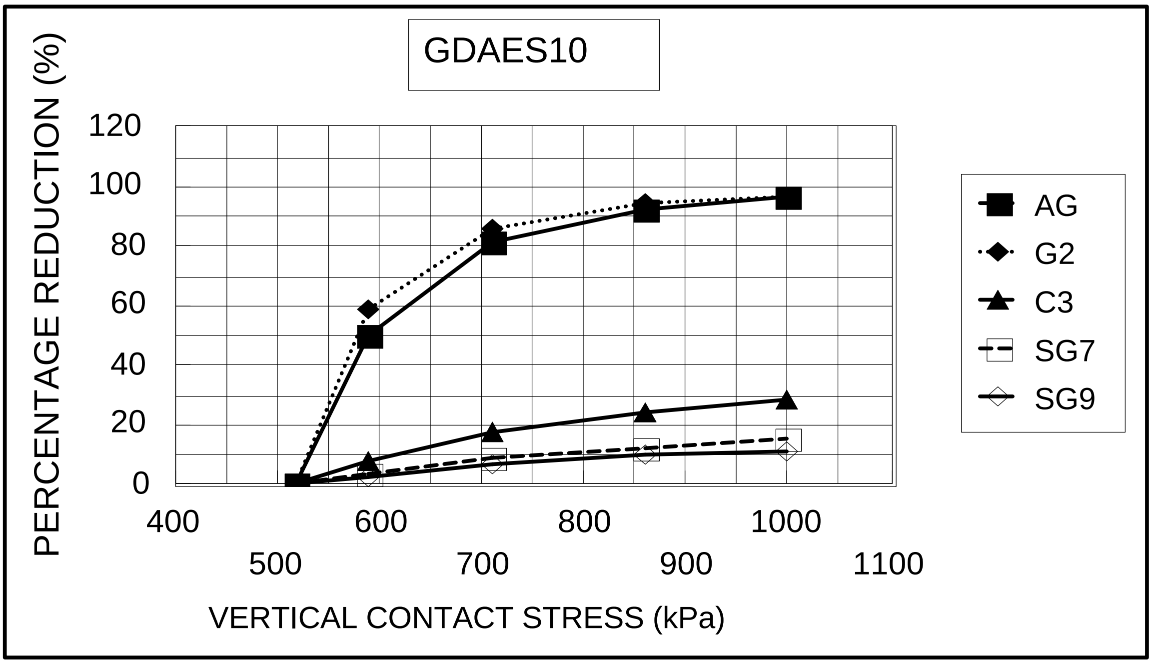


Figure 3: Percentage Reduction in Calculated Layer Life As A Result of Increased Contact Stress on Pavement GDAES10 (GDAES10: Granular Base, Dry, Category A, Traffic Class: ES10 (TRH 4, 1996) The layer codes AG; G2; C3; SG7; SG9 are from TRH 4 (1996)).

The main *conclusions* drawn from the above study were:

- ♦ Increased tyre/pavement contact stresses potentially *accelerate* deterioration of the *surfacing and base layers* of most of the flexible pavements contained in the catalogue of the new Draft TRH 4 (1996) designs. Note: This may explain some of the more serious surfacing distresses noted on many pavements in South Africa today.
- ♦ Secondly, the study indicated that *increased axle loads* would potentially damage the *lower layers from the subbase downwards*, that only increases in layer thickness and/or improvement of material quality would reduce potential damage in this regard.

The following were *recommended* by the above study:

- ♦ Further refinement of the South African Mechanistic Design Method (SAMDM) to include modelling of non-uniformly distributed vertical and shear stresses on the surface of flexible pavements (i.e. improved definition of tyre/pavement contact stress);
- ♦ Repeat of the study discussed in a report by De Beer (1998) with an improved definition of tyre/pavement contact stress on selected pavement structures;
- ♦ Future research to concentrate on the mechanistic evaluation of flexible thin surfacing layer design and performance of typical South African pavement structures.
- ♦ Road authorities to take cognisance of the results of this study for the purposes of

combatting the effect of increased contact stresses and heavier axle loads on the road networks under their jurisdiction.

2.4 Discussion on Research approach for Asphalt material

In order to facilitate effective research and implementation, it is strongly felt that a definite distinction should be made between (i) those efforts that are directed towards fundamental understanding of pavement distresses in the longer term (i.e. those aimed at identifying and clarifying distress mechanisms and first order causes) and (ii) those efforts that are directed at developing practical and cost - effective methods in the shorter term for detection and prevention of (premature) distresses at both the asphalt hot mix and pavement design stages. However, both of these objectives should be addressed but, in the context of a typical medium - term project aimed at, for example, improving asphalt mix design and mix evaluation methods (such as the HMA , 1998 project), the objective (ii) noted above, is perhaps more urgent.

In order to try and understand rutting problems of asphalt layers in accordance with objective (i) given above, it is critical that applied *tyre loads and tyre/pavement contact stresses* on pavements should be known and *quantified*. Once this is known, improved laboratory test methods can be devised in order to quantify the more *fundamental engineering characteristics* of plastic deformation of asphaltic materials, such as the:

i) *Pure volumetric changes* where there is a reduction in the effective void content in the pavement layers (asphalt and/or granular), and

ii) *Pure shape distortion* where the volume (i.e. effective void content in the mix or layer) remains constant, leading to “shoving” of the hot mix asphalt or shearing of granular base layers which are usually protected with thin (< 50 mm) asphaltic surfacings.

There should also be a dedicated effort to establish the *fundamental reasons* for the types of distress given in Table 3 before more rational mechanistically based prediction methods and linking of behaviour with performance can be made available to practice.

One of the important issues mentioned above is the “real world” tyre/pavement contact stresses. This is discussed in detail in the next section.

3 IMPLEMENTATION OF SIM TECHNOLOGY: DEMONSTRATION PROJECT AT MANTSOLE TRAFFIC CONTROL CENTRE (TCC) ON THE NATIONAL ROAD NUMBER 1 (N1)

The aim of this paper is to illustrate some of the first results of the demonstration project where SIM technology was applied to the traffic control centre (TCC) at Mantsole, on the N1 north of Pretoria. As stated earlier, a new SIM system was developed and build by Transportek in association with The South African National Roads Agency Ltd. (SANRA). The new VRSPTA system will be used in future at Mantsole TCC, mainly for “real world” data collection on the 3 dimensional (3-D) contact stresses under real trucks using the N1. The SIM system was installed on site during November/December 1998, and “real world” contact stress data of typical heavy trucks were measured over a period of several days. This new system consists of four similar measuring units which are typically installed in the road base flush with the surface of the pavement. They are designed to measure the 3-D contact stresses under all the tyres of one axle of a vehicle, simultaneously. A typical layout of the new VRSPTA Mark III SIM system at Mantsole, with a truck axle is shown in Figure 4.

3.1 Examples of VRSPTA SIM measurement during β - Testing

Examples of the measurements for a light commercial vehicle (Hi-Ace) and the Deflectograph that were made during the β - Testing on CSIR campus are given below. The Deflectograph with a 45 kN front axle (600 kPa tyre inflation pressure), and 80 kN rear axle (690 kPa tyre inflation pressure) belongs to Transportek of the CSIR and is used to obtain the left and right deflection basins at a speed of 5 km/h on normal paved roads. Typical results from the new SIM system (VRSPTA Mark III), where the 3 dimensional contact stresses were measured simultaneously of the 2 axle, four wheel light commercial vehicle (Hi-Ace) and the two axle, six wheel Deflectograph truck are illustrated in Figure 5.

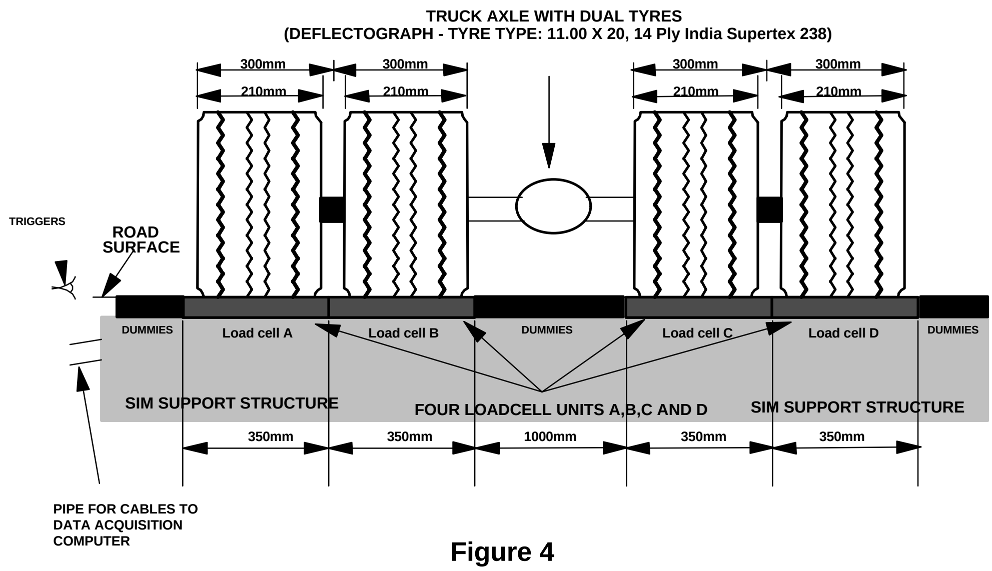


Figure 4

TYPICAL LAYOUT OF THE VRSPTA MARK III SIM SYSTEM WITH A TYPICAL TRUCK AXLE (DUAL TYRES)

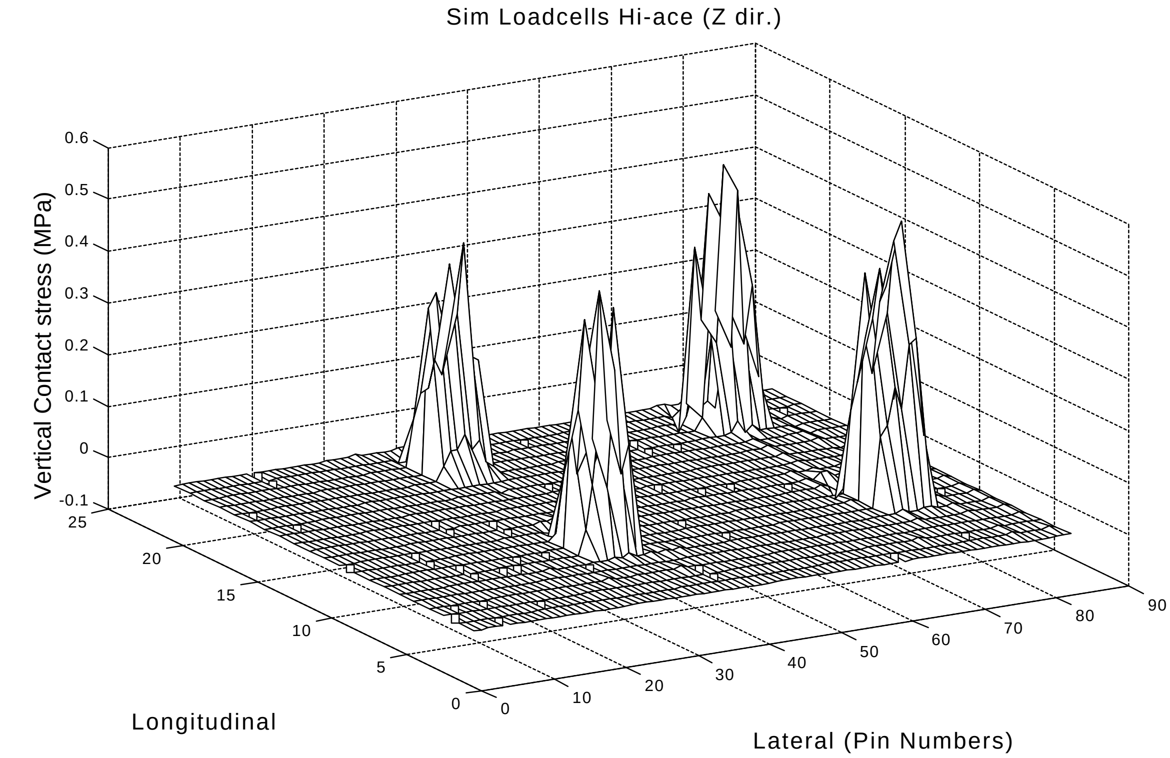


Figure 5a: Hi-Ace: Vertical contact stress under the four tyres (Inflation Pressure = 400 kPa)

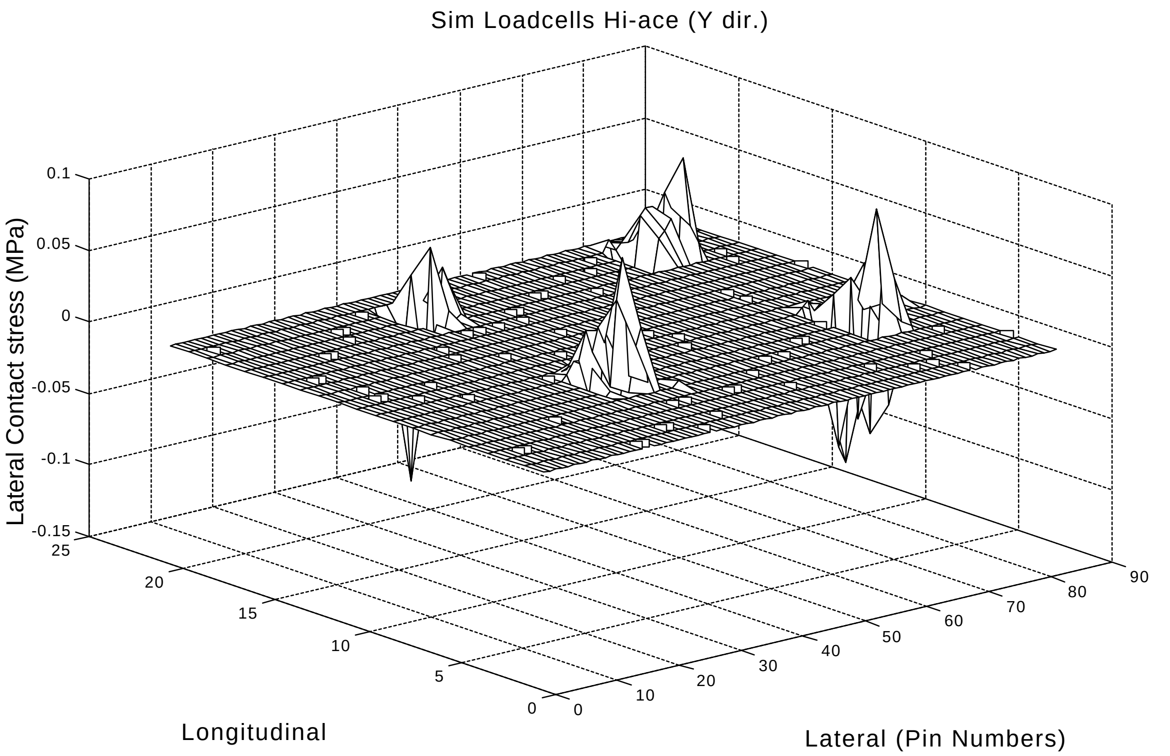


Figure 5b: Hi-Ace: Lateral contact stress under the four tyres (Inflation Pressure = 400 kPa)

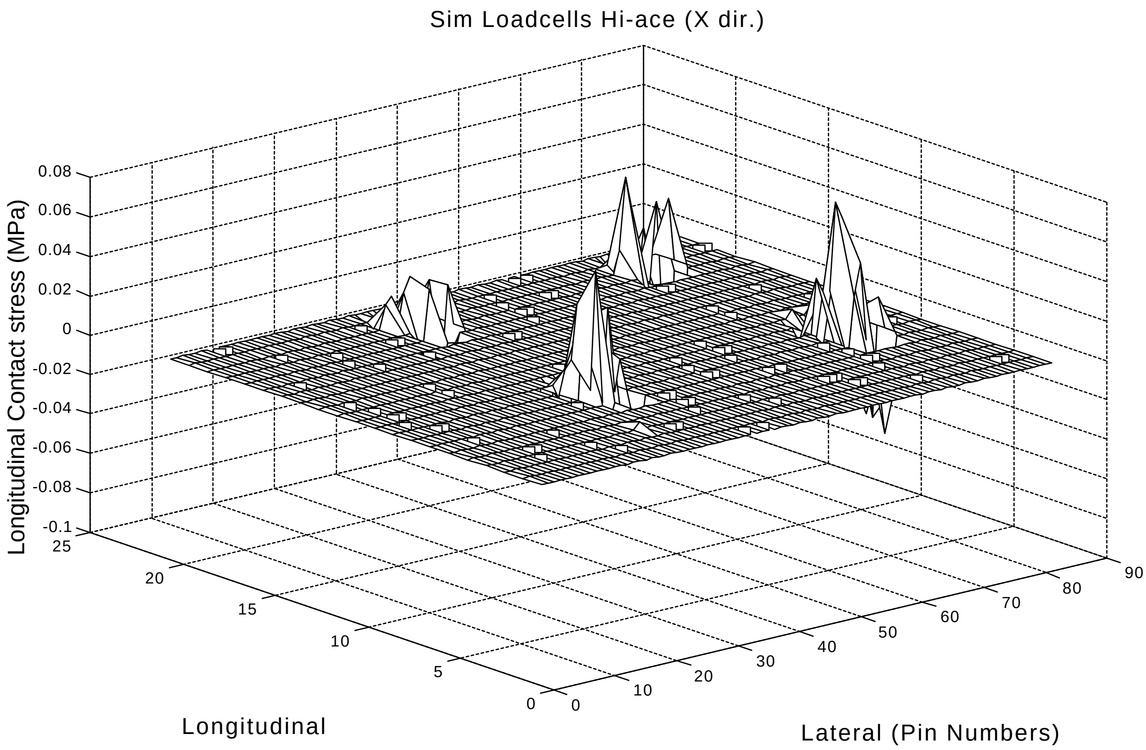


Figure 5c: Hi-Ace: Longitudinal contact stress under the four tyres (Inflation Pressure = 400 kPa)

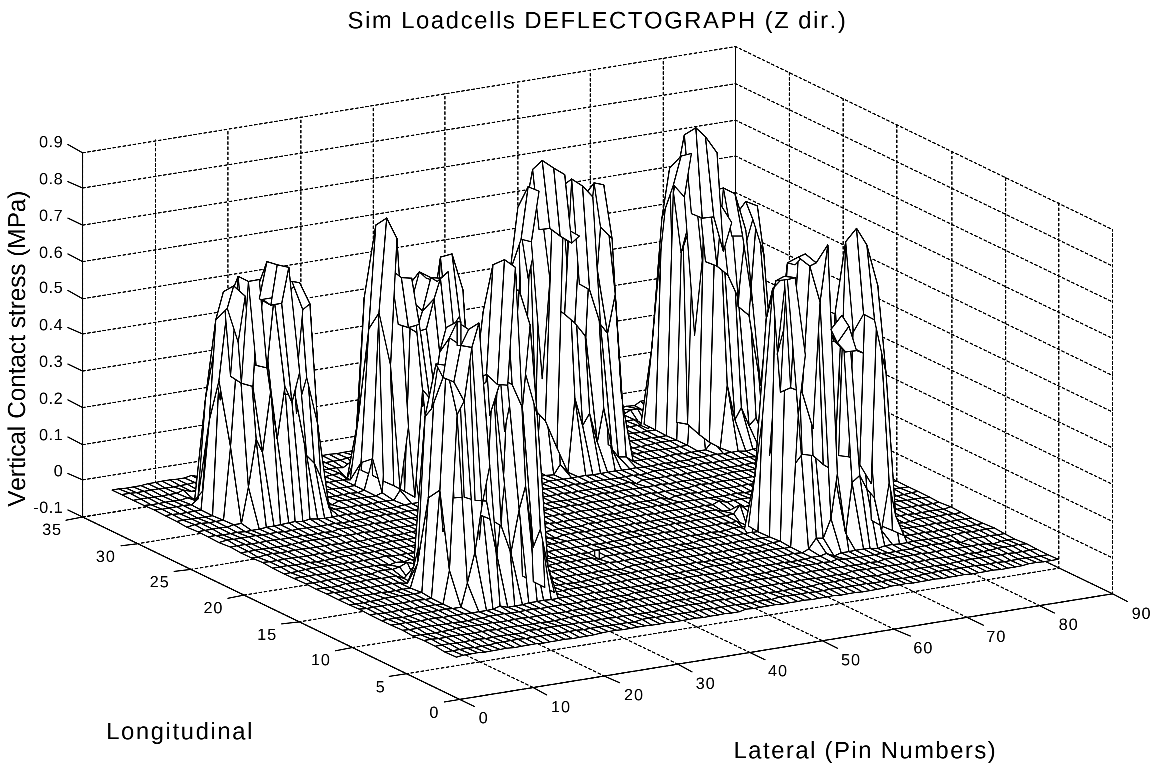


Figure 5d: Deflectograph: Vertical contact stress under the six tyres (Inflation Pressures: Front = 600 kPa; Rear = 690 kPa)

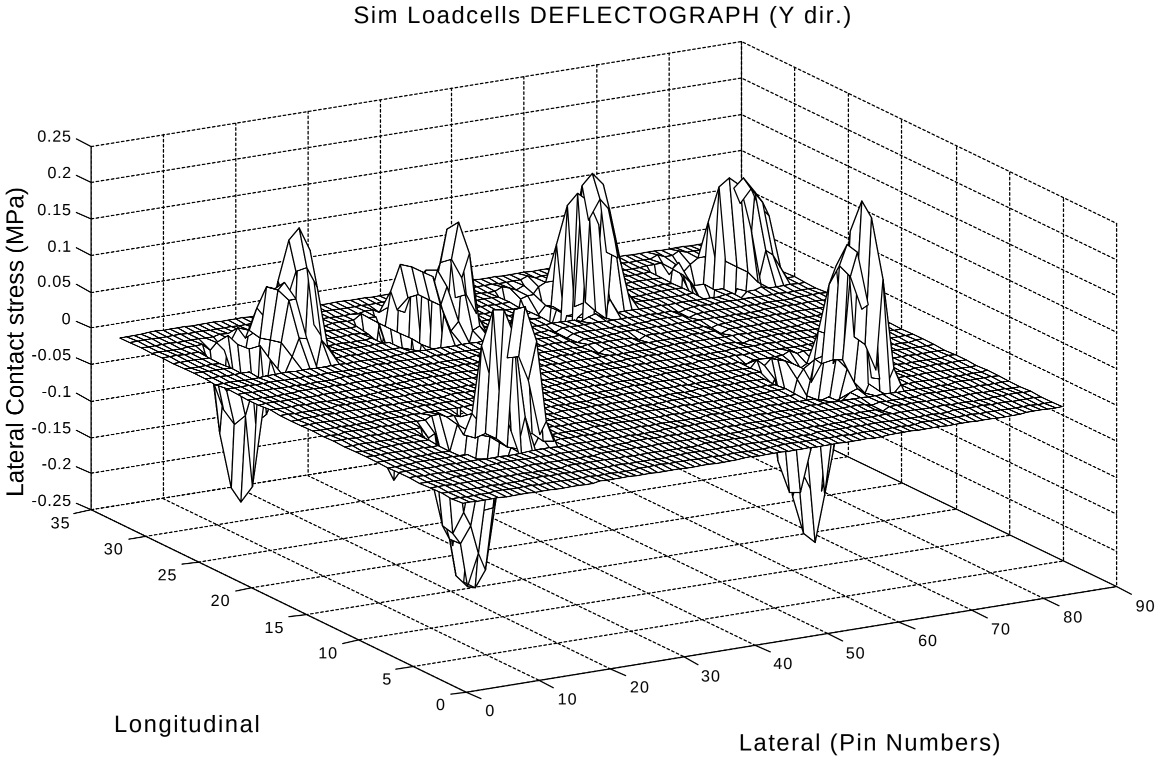


Figure 5e: Deflectograph: Lateral contact stress under the six tyres (Inflation Pressures: Front = 600 kPa; Rear = 690 kPa)

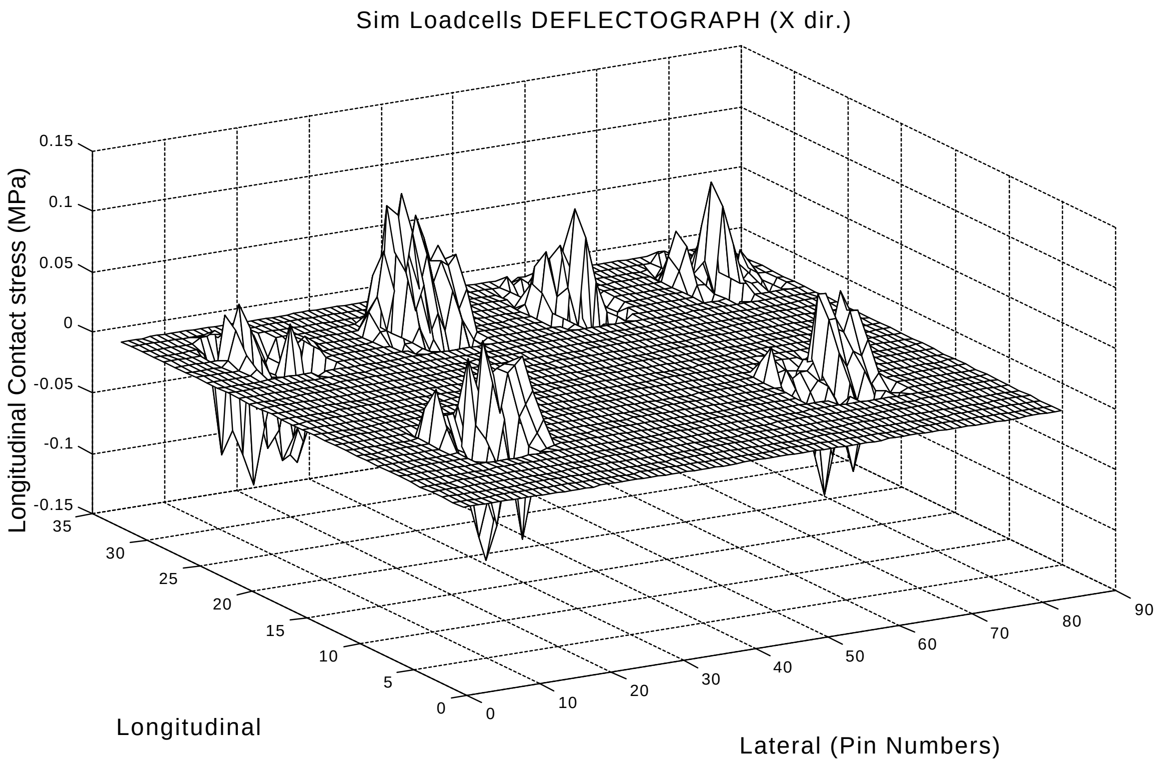


Figure 5f: Deflectograph: Longitudinal contact stress under the six tyres (Inflation Pressures: Front = 600 kPa; Rear = 690 kPa)

Figure 6 illustrates a cumulative frequency distribution of the SIM measured results from the Deflectograph during the 2nd β - testing on CSIR campus during October 1998. It is clear from the figure that the currently accepted level of 520 kPa for pavement design purposes for an axle load of 80 kN is *too low*, since it only provides for less than the 50th percentile of the actual vertical contact stress. The figure further shows that vertical contact stresses in the range of 700 kPa to 900 kPa, with a maximum of 1150 kPa, seems more appropriate for a design vehicle such as the Deflectograph.

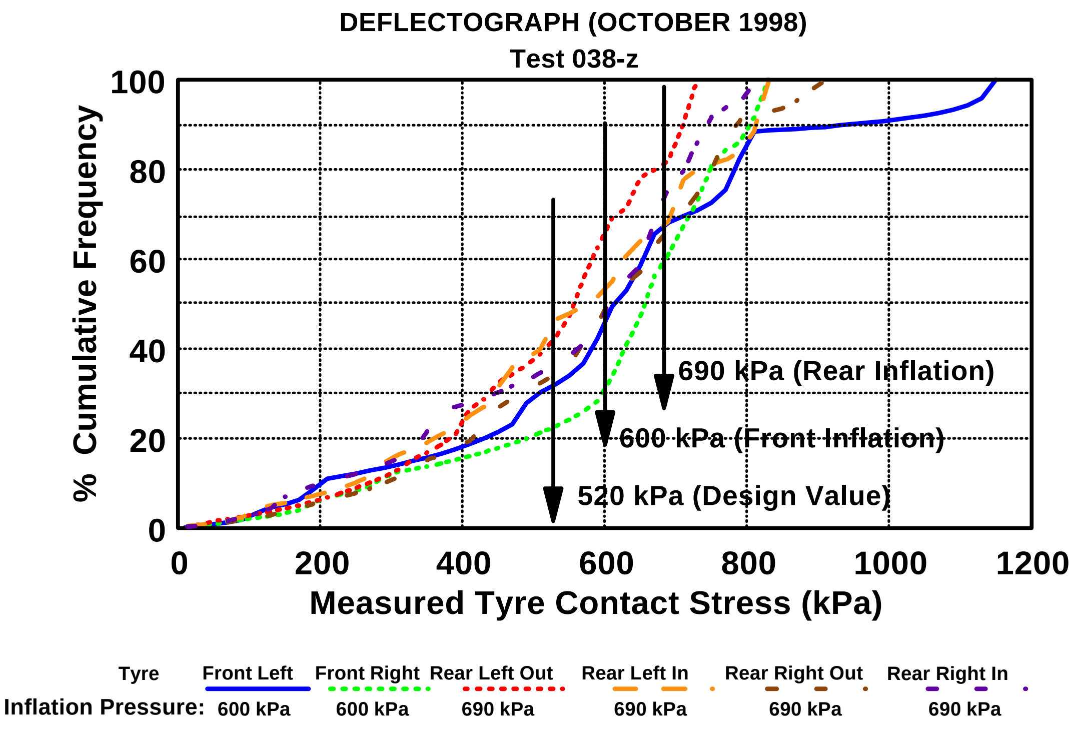


Figure 6: Cumulative Frequency of the measured tyre contact stress of all tyres of the Deflectograph (Test 38 - October 1998, 2nd β - testing, CSIR)

3.2 Example of VRSPTA SIM measurements at Mantsole, TCC

The cumulative frequency of a typical 7-axle truck (type: 1:2:2:2) that was measured at Mantsole is illustrated in Figure 7. As with Figure 6, the data clearly demonstrate that the actual vertical contact stresses vary from tyre to tyre, and also that the magnitude of these stresses ranged from 650 kPa to 1250 kPa, maximum. (Note that in Figure 7 only 23 of the 26 tyres measured are shown, owing to limitations in the graphical computer package used for the graph). The measured data for this truck are summarised in Appendix A. The results in Appendix A include the following details of the measured truck:

a. Tyre width;
b. Tyre area;
c. Contact patch length (TPL);
d. Maximum Stresses: Vertical, Lateral, Longitudinal;
e. Maximum Stress Ratios; (Vertical : Lateral : Longitudinal);
f. Tyre weights;
g. Axle weights;
h. Axle Group weights;
i. Axle Speed;
j. Axle distance;

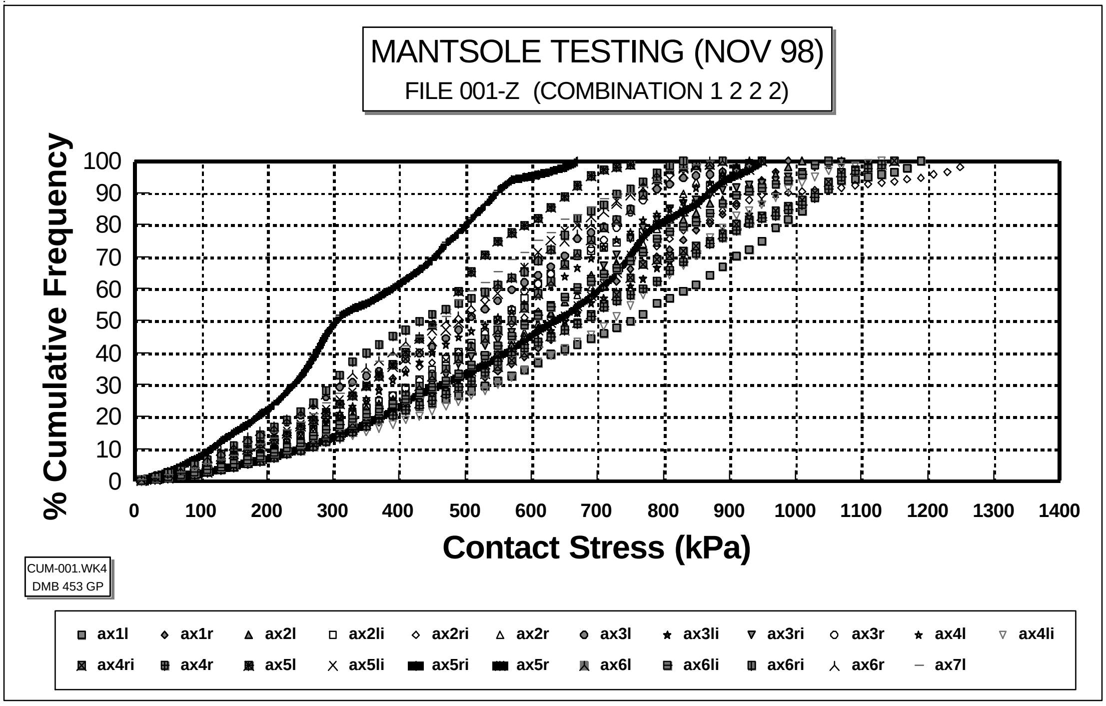


Figure 7: Cumulative Frequency of the measured tyre contact stress of all tyres of a typical 7-axle (1:2:2:2) truck at Mantsole (Test 001-Z - November 1998 - N1, Mantsole). The solid lines represent the right inner (ax5ri) and the right outer (ax5ro) tyre of axle number 5, ax5ri showing the lower stresses. See also Figure 8 below.

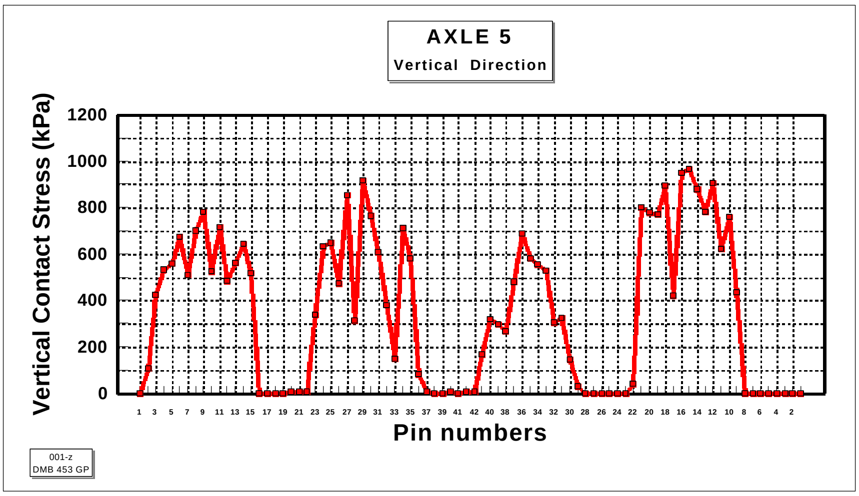


Figure 8: Maximum Vertical contact stress of all four tyres on axle number 5 of the 7-axle truck, given in Figure 7. Note the relatively lower stresses of the right inner (ax5ri) tyre.

3.4 Vertical Stress distribution between dual tyres

In Figure 8 the measured vertical stresses of axle 5 of the above truck are shown. It is clear that the vertical contact stresses produced by the two right hand tyres (i.e. axle number 5, right inner (ax5ri) and axle number 5, right outer (ax5ro)) are *not* equal. The tyre loads were also very different: 1000 kg for ax5ri and 2500 kg for ax5ro. For tyre ax5ri the vertical stress varied from 0 to 670 kPa, and for tyre ax5ro the range is 0 to 940 kPa. This indicates a difference of up to 40 per cent between the maximum stresses obtained from these two tyres. See also Figure 7 for the cumulative distribution of the vertical contact stresses.

The stress (and load) difference between the dual tyres given here illustrates the potential for non-equal loading on typical “real world” trucks. Future research should concentrate on methods whereby this effect could also be introduced during the design and analysis of flexible pavement structures.

3.5 Discussion of VRSPTA Mark III SIM results so far

The information obtained from “real world” conditions (i.e. normal trucks) should serve as the new design input guidelines for improved mechanistic-empirical design and analysis of South African pavements. In the long term it is hoped to generate more data on other TCC localities in South Africa in order to better define representative tyre/pavement contact stress patterns on South African roads.

Further, it is believed that, with the new knowledge generated in this way, the gap between observed distress patterns, material properties/mechanistic design procedures and laboratory testing could be narrowed. In principle, more cost-effective pavement design, construction and rehabilitation should therefore be possible if the actual contact stresses are taken directly into consideration.

However, more focus is also needed in order to design and develop alternative laboratory test methods which enable these contact stresses as well as the basic behaviour/distress patterns found on actual pavements to be simulated. This might be the only way to bridge the gap between existing design and analysis methods, especially for more economical road surfacings and maintenance.

4 MECHANISTIC PAVEMENT DESIGN AND ANALYSIS ISSUES

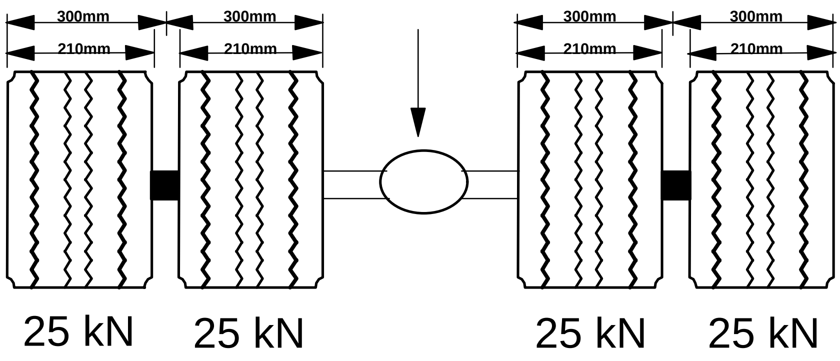
4.1 Interim Design Contact Stress and Load values

The current conventional linear elastic multi-layer solution (Linear Elastic Theory, LET) does not cater for non-uniform and three - dimensional load/stress conditions. Ideally, in order to provide for improved mechanistic design and analysis of flexible pavement systems, it is necessary to replace the current standard circular disc of 520 kPa uniform contact stress with the VRSPTA measured three - dimensional contact stress data as input. Since this is currently a difficult option, an interim recommendation for improved vertical contact stress values and axle (and tyre) loads for the mechanistic design and analysis procedures was made. These proposed new values are given in Table 5 below, for the four road categories given in Draft TRH 4 (1996). It is proposed to use a design axle of 100 kN in addition to the standard 80 kN axle, in view of the new load legislation in South Africa.

Table 5: Recommended Interim Vertical Contact Load/Stress values for Mechanistic Design and Analysis

DEFLECTOGRAPH TRUCK AXLE WITH DUAL TYRES
(TYRE TYPE: 11.00 X 20, 14 Ply India Supertex 238)

100 kN Axle



Road Category (TRH 4, 1996)	Design Percentile Value	Circular Vertical Contact Stress (kPa)	Circular Load Radius (mm)
A	95	950	91,5
B	90	850	96,7
C	80	750	103,0
D	50	650	110,6

It is recommended that the values in Table 5 be used until further research proves otherwise, *in addition* to the traditional 520 kPa, 20 kN, which should be used for reference purposes.

4.2 Finite Element Method (FEM)

The Finite Element Method (FEM) is the only way in which the VRSPTA measured stresses can be used as load/stress input for the design and analysis of pavement structures. Recent work by Jooste and Lourens (1998) and a detailed study by Groenendijk (1998) indicated that the non-uniformity of the contact stresses as well as the shape of the contact area played a significant role in the development and magnitude of the tensile strain in flexible pavement systems. It was shown that the conventional LET models, with a uniform circular contact stress potentially underestimate the maximum horizontal tensile strain by as much as 100 per cent. For rutting, when the octahedral shear stress in the asphalt layer was used as a criterion, underestimations of up to 20 per cent were calculated. This was due in part to the shape of the contact stress according to Jooste and Lourens (1998). In addition to the issue of contact stress and load definition, new or alternative damage criteria need to be developed especially for asphalt pavement layers. Earlier work (De Beer et al, 1997) indicated that the strain energy of distortion (SED) seemed to pinpoint potential damage locations within thin asphalt surfacings more realistically than the well known tensile strain criterion. In Figures 9 and 10 an indication of the SED for a thin asphalt pavement is illustrated, in which the normal circular LET method (Figure 9) is compared with a non-uniform vertical contact stress with lateral shear (Figure 10) (De Beer, et al, 1997). The non-uniformity of the tyre contact stress complicates the idealization of contact stresses for flexible pavement analysis purposes. To date, the most efficient way to utilize these non-uniform and shear stresses as input values in pavement analysis is to make use of the Finite Element Method (FEM).

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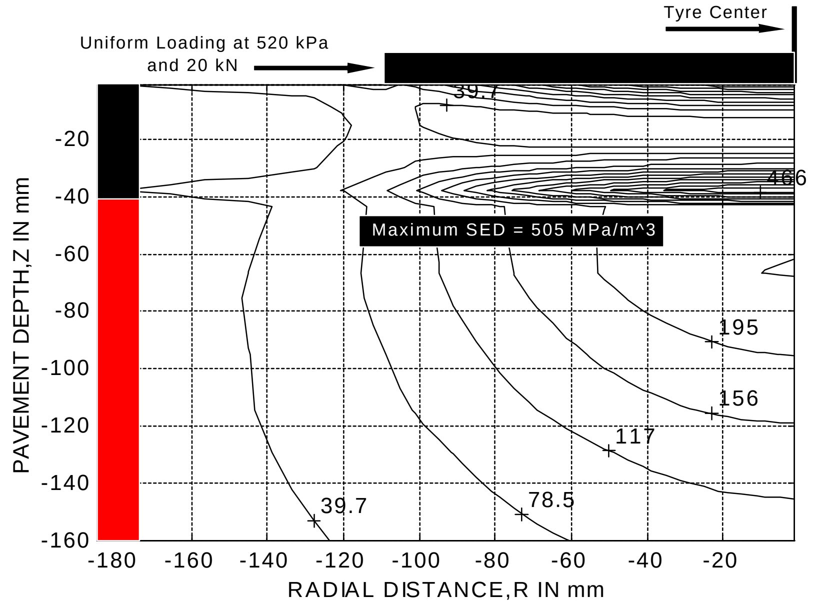

Figure 9: Image of strain energy of distortion (SED) under a uniform contact stress of 520 kPa. Note that only half of the pavement section with the vertical load is shown here, with the centre of the loading on the right side of image. The disc shaped area at a depth of 38 mm near the right side of the image indicates the maximum SED under the tyre centre in the asphalt.
(After De Beer et al, 1997).

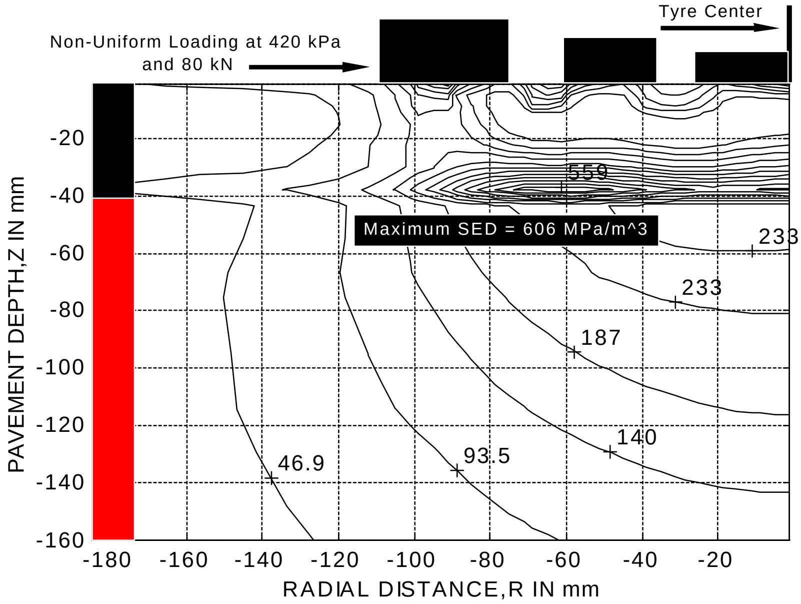

Figure 10: Image of strain energy of distortion (SED) under non-uniform contact stress conditions. Note that only half of the pavement section with the non-uniform vertical load is shown here, with the centre of the loading on the right side of image. The disc shaped area at a depth of 38 mm towards the edge of the tyre loading in the centre of the image indicates the maximum SED under the tyre edge in the asphalt. (After De Beer et al, 1997).

Recent FEM studies (De Beer et al, 1997b; Symplectic Engineering Corporation, 1997; Weissman , 1997; Jooste and Lourens, 1998; Merrill et al, 1998) indicate that this method indeed provides for improved definition of the stress and strain conditions in the near - surface pavement section. These studies indicated the following findings:

- Development of significant tensile strains and stresses close to the outside of the tyre edge, and compressive stresses and strain inside the tyre contact patch;
- Highly non-uniformly distributed stress and strain patterns in the top 50 mm to 75 mm of the pavement;
- The importance of separation of volume changes from shape distortion in the top 50 mm to 75 mm of the pavement, especially near the tyre edges;

An interesting development in the analysis and presentation of results is the use of computer generated visual colour maps of pavement response parameters such as the "energy" (stress x strain), or shape distortion such as the square root of the second invariant of the strain tensor (J_2) inside multi-layered pavement sections. These presentations greatly enhance the understanding of tyre/pavement interaction. As an example, an analysis done by Symplectic Engineering Corporation (1997) using a typical VRSPTA measured 3-D non-uniform contact stress distributions on three layer pavements yielded the graphical results illustrated in Figures 11 and 12.

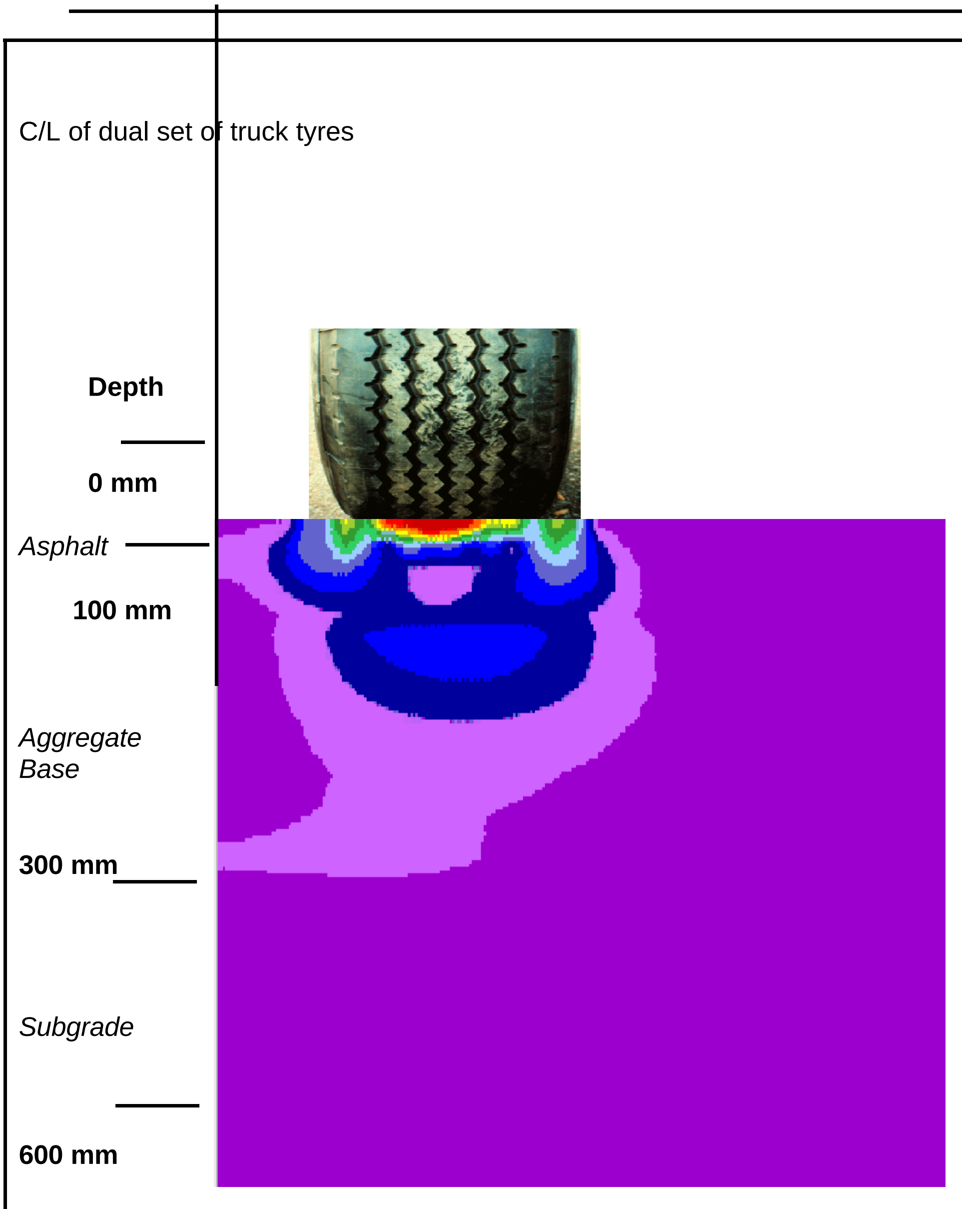

Figure 11: Qualitative contour map of Pseudo-Energy (stress x strain) in three layered flexible pavement system. Note: Only ½ of a dual tyred load shown here, note also the maxima of the energy at the tyre edges (modified after Symplectic Engineering Corporation, 1997).

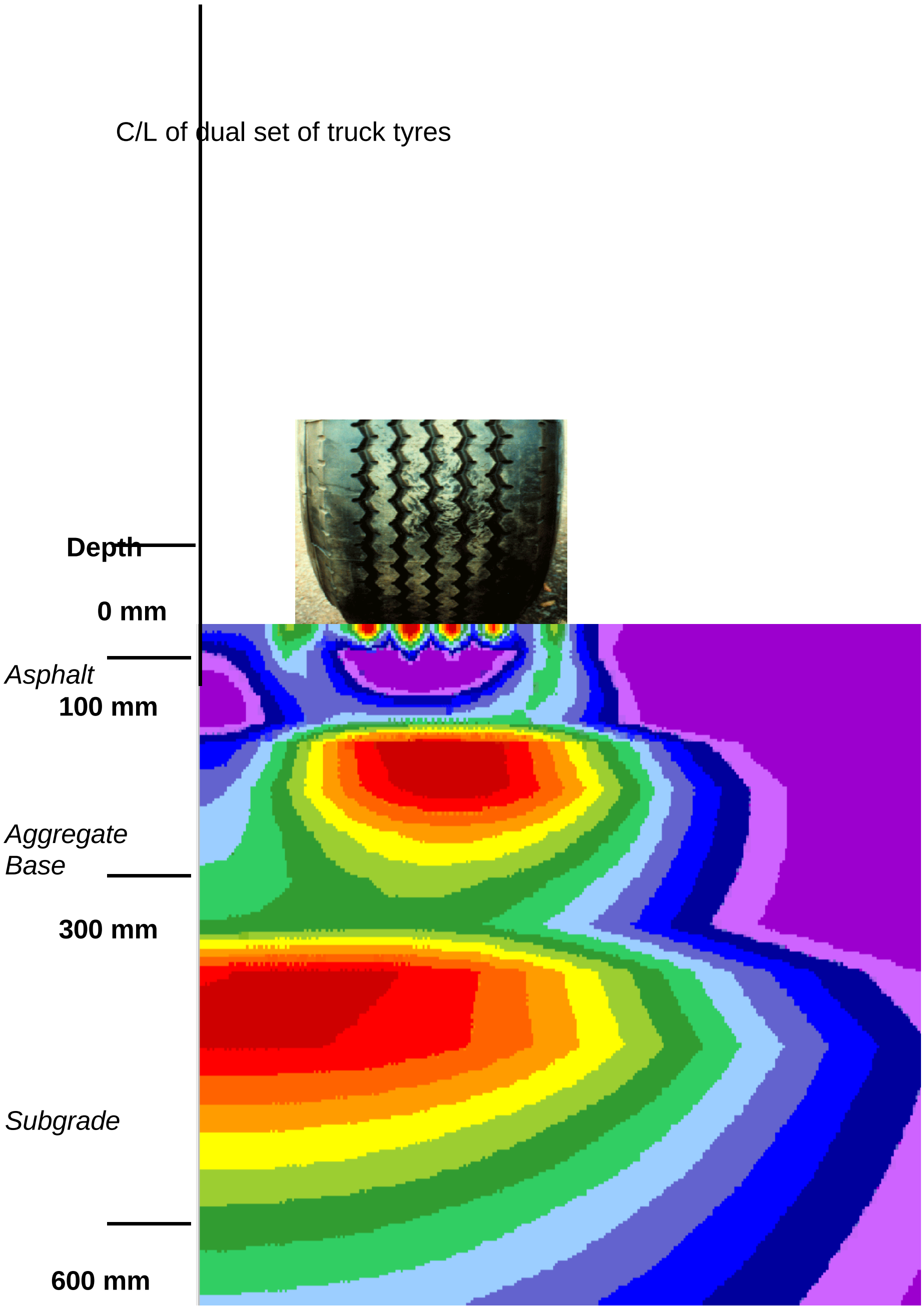

Figure 12: Qualitative contour map of shape distortion in a three layered flexible pavement system defined by the square root of the second invariant of the strain tensor (J_2). Note: Only ½ of a dual tyred load shown here, and also note the irregular shape distortion near the surface in the asphalt layer under the tyre (modified after Symplectic Engineering Corporation, 1997).

5 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

In this paper the issue of three - dimensional tyre/pavement contact stresses of slow moving "real world" vehicles is discussed. These stresses are measured using a South African developed system, referred to as the **Vehicle-Road-Surface-Pressure-Transducer-Array (VRSPTA).** The VRSPTA system is essentially a Stress - In - Motion (SIM) system, which measures the three - dimensional contact stresses of all the tyres of slow moving vehicles. Both the measurement and analysis of tyre/pavement contact stresses and the possible effects of these on flexible pavement systems are discussed. In addition to improved understanding of "real world" contact stresses, current national and international information hints towards a greater need to understand pavement surface distresses at the tyre/pavement interface. Growing evidence points to many failures associated at the top and on the surface of flexible pavement systems. Improved understanding of the asphalt materials both in the laboratory and the field is therefore needed, which also forms the basis for the recent hot mix asphalt (HMA) project in South Africa. The paper indicates that the traditional 520 kPa, 20 kN load/stress idealization used for flexible pavement design is outdated and should be replaced by higher values. Contact stresses in the range of 700 kPa to 800 kPa are more appropriate for a vehicle such as the Deflectograph truck of the CSIR. The results under a typical 7-axle truck at Mantsole TCC show that maximum vertical stresses vary from 650 kPa to 1250 kPa for all the tyres measured. The VRSPTA results also indicated non-equal load and stress distribution between a dual set of tyres on the 7-axle truck. This is indeed an area for future research. Owing to the increase in legal axle loads and the level of overloading in South Africa it is also considered advicable to use a tyre load of 25 kN *in addition* to the traditional value of 20 kN for routine pavement design and analysis.

Finally, the measured data illustrate the basic shapes of the contact stress distribution found with the VRSPTA SIM system, with some examples found on a typical National Freeway in South Africa. In addition, the paper also demonstrates alternative modelling methods where the SIM measured results are applied in the design and modelling of pavements with relatively thin (<50 mm) asphalt surfacings.

5.2 Conclusions and Recommendations

The following is concluded from this study:

- Three - dimensional tyre/pavement contact stresses of slow moving pneumatic tyres can be measured effectively under "real world" vehicles and conditions;
- Opinions and road needs studies have found that there is little commonality between surface distress types on South African roads, mechanistic pavement design analysis, laboratory test results, predictions and material properties;
- Tyre inflation pressures of heavy trucks in South Africa have increased by approximately 20 per cent during the period 1974 to 1995;
- Studies on overloading indicated that of the approximately 90 000 vehicles weighed in 1997, 35 per cent were overloaded in terms of the new load legislation;
- It is believed that improved description and quantification of the tyre/pavement contact stresses and loads could provide key information in attempts to narrow the

gap between observed pavement surface distresses and mechanistic predictions, analysis and laboratory test methods and procedures;

- Limited studies so far indicate that more advanced mechanistic analysis methods incorporating advanced materials and load/stress models are not currently available, and should be developed;
- The current level of 520 kPa and 20 kN mechanistic design stress/load conditions should be revised to include the higher levels reported in this study;
- Non-equal load and vertical contact stresses were found for a dual tyre set on a typical 7-axle truck. A contact stress difference of up to 40 per cent was measured between the dual tyres;
- Improved mechanistic models should be developed for the improved prediction of pavement performance. This should be done by an improvement of both the material modelling (constitutive models), as well as of improved definition of tyre/pavement contact stress and load.
- It is also concluded that the information obtained so far is considered vital for the improved design and maintenance of flexible road systems. It is believed that the VRSPTA technology has great potential for use in *"Stress-In-Motion" (SIM)* measurement systems for possible integration with current *Weigh-In-Motion (WIM)* technologies in South Africa. This, however, was not treated as part of this paper as it is seen as a separate topic. In addition, further implementation of the SIM technology may result in improved *traffic control measures* through improved quantification of the traffic loading and contact stresses between individual truck tyres and the pavement surface, which will assist with improved policing particularly of overloading and also of over - inflation of individual truck tyres and axles.

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APPENDIX A
MEASURED DATA (SEE FOLLOWING TWO TABLES) FROM THE VRSPTA MARK III SIM MEASUREMENTS OF A 7-AXLE TRUCK (1:2:2:2) AT MANTSOLE TRAFFIC CONTROL CENTRE (TCC)

Table A1: Examples of the two output reports (*TAS and *.LDS files) produced on site from the VRSPTA Mark III system at Mantsole TCC

C:\SIMVLT\001-1.TAS
25/Nov/1998 12:18:31
Vehicle Registration : dmb453gp
Aggregate Rate : 64103
CGLSize : 64
Number of Axles : 7

Axle	SPA [s]	EPA [s]	SPB [s]	Speed [m/s]	Duration [s]
1	0.047	0.593	0.639	1.689	0.546
2	2.086	2.562	2.585	2.003	0.476
3	2.776	3.228	3.277	1.995	0.452
4	5.905	6.338	6.387	2.078	0.432
5	6.528	6.960	7.009	2.082	0.431
6	8.690	9.235	9.218	1.893	0.545
7	9.472	9.947	9.977	1.979	0.475

C:\AXWGTS\001.LDS PROGRAM -- WHEELS-2X
25/Nov/1998 12:18:31
Reg. Number : dmb453gp

Axle Num	Axle Dist. [m]	W-Weight Left Tonne	W-Weight Right Tonne	Axle Weight Tonne	TPL 1 mm	TPL 2 mm	TPL 3 mm	TPL 4 mm
1		2.156	2.405	4.561	296	0	320	0
2	3.764	4.013	4.234	8.248	281	263	323	261
3	1.379	4.018	4.118	8.136	274	290	436	246
4	6.372	4.161	4.349	8.51	277	311	833	306
5	1.296	3.488	3.507	6.995	274	276	413	600
6	4.297	4.435	2.601	7.036	290	494	304	251
7	1.514	3.298	3.734	7.032	268	278	920	282

Table A2: An example of the analysis layout of the Lotus 1-2-3 summary file (*.WK4) for each truck measured and analysed

LDS001.WK4 **Combination (1 : 2 : 2 : 2)**
DMB 543 GP
25/11/98

Tyre	Tyre width (mm)	Tyre area (mm^2)	Patch Length (mm)	Maximum Contact Stress Vertical kPa	Lateral kPa	Long. kPa	Maximum Stress Ratios Vertical	Lateral	Long.	Tyre Weights (kg)	Axle Weights (kg)	Axle Group (kg)
fl	204	52288	290	1199	252	152	10.0	2.1	1.3	2200	4600	4600
fr	187	55499	322	999	184	96	10.0	1.8	1.0	2400		
ax2lo	221	58338	278	1019	172	108	10.0	1.7	1.1	2200	8200	
ax2li	187	46745	266	955	152	116	10.0	1.6	1.2	1800		
ax2ri	187	53850	320	1275	288	180	10.0	2.3	1.4	2200		16300
ax2ro	221	53918	258	947	124	72	10.0	1.3	0.8	2000		
ax3lo	238	56886	275	967	184	144	10.0	1.9	1.5	1600	8100	
ax3li	221	60306	291	1087	240	144	10.0	2.2	1.3	2400		
ax3ri	221	56344	269	1115	252	232	10.0	2.3	2.1	2300		
ax3ro	187	43951	245	887	104	84	10.0	1.2	0.9	1800		
ax4lo	187	44228	270	927	136	84	10.0	1.5	0.9	1400	8400	
ax4li	204	60099	311	1159	176	136	10.0	1.5	1.2	2700		
ax4ri	170	45497	288	1179	168	60	10.0	1.4	0.5	2200		15400
ax4ro	170	47966	305	1163	172	60	10.0	1.5	0.5	2100		
ax5lo	238	57882	266	783	160	44	10.0	2.0	0.6	1700	7000	
ax5li	221	56045	270	915	136	60	10.0	1.5	0.7	1800		
ax5ri	187	40814	231	687	116	124	10.0	1.7	1.8	1000		
ax5ro	221	59720	281	963	124	92	10.0	1.3	1.0	2500		
ax6lo	204	55905	289	915	204	92	10.0	2.2	1.0	2100	7000	
ax6li	204	57447	306	1067	196	140	10.0	1.8	1.3	2300		
ax6ri	187	46298	304	855	232	120	10.0	2.7	1.4	1300		14100
ax6ro	204	43953	244	895	220	76	10.0	2.5	0.8	1300		
ax7lo	204	47965	269	891	140	64	10.0	1.6	0.7	1400	7100	
ax7li	204	53608	283	991	172	92	10.0	1.7	0.9	1900		
ax7ri	204	56429	304	851	332	112	10.0	3.9	1.3	2200		
ax7ro	187	47663	279	1023	196	44	10.0	1.9	0.4	1600		
											TOTAL WEIGHT	50400

fl = Front Left **fr = Front Right** **ax = axle** **2 = Axle Number** **l = Left** **r = Right** **o = Outer** **i = Inner**