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DETERMINATION OF PNEUMATIC TYRE/PAVEMENT INTERFACE CONTACT STRESSES UNDER MOVING LOADS AND SOME EFFECTS ON PAVEMENTS WITH THIN ASPHALT SURFACING LAYERS

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Abstract. This paper describes the quantification of three-dimensional tyre/pavement contact stresses for vehicle tyres. The Vehicle-Road Surface Pressure Transducer Array (VRSPTA) system was developed to measure contact stresses under moving loads, i.e. Stress-In-Motion (SIM). Prediction equations for quantification of these stresses, based on tyre inflation pressure and loads for seven (7) different tyre types, are given. Tyre inflation pressure predominantly controls the vertical contact stresses on the pavement at the tyre centre, whereas the tyre load controls those at the tyre edges. Analysis indicated that during instantaneous overloading/under- inflated conditions the maximum strain energy of distortion (SED) in the asphalt surfacing occurs close to the tyre edges, while under instantaneous uniform vertical stress conditions the SED is within the asphalt surfacing at the tyre centre. In addition to improved load/contact stress idealization for modelling, this finding may have important implications for the design of relatively thin asphalt surfacing layers for pavements.

Keywords. Pavement, surfacing, distress, tyre, measurement, contact stress, Stress-In-Motion (SIM) design, analysis.

INTRODUCTION

It is well known that there is an increasing trend towards higher traffic volume and traffic load demands on existing road and/or pavement network systems worldwide. These network systems are undoubtedly recognized by most governments in the civilized world as the necessary arteries for the sustainable and consistent economic growth of a country. Therefore, it is of vital importance not only to plan ahead for future growth (i.e. the building of new roads), but also to invest in efficient rehabilitation and upgrading policies for the preservation of existing road networks. In a recent study by Maasdorp (1996), the implications for the transport policy and infrastructure of South Africa in a new world of trade are discussed. It is clear from this study that South Africa has "come in from the cold" and that its foreign trade is expanding rapidly, especially with its Southern African Customs Union (SACU) partners. During the period 1991 to 1993 the total road export/import trade tonnages with the rest of Africa increased by approximately 34 per cent In terms of volume of trade, Europe and Asia seem to be the most important, which directly influences the routes to and from South Africa's harbour areas. This increased trade therefore directly influences the total transport sector, and hence the infrastructure. In order to develop adequate transport policies, quality technical information is necessary and should focus on real practical issues relating directly to the road user and the road authority tasked with the design, construction, maintenance and rehabilitation of the transport infrastructure. This necessitates a structural/functional life cycle approach to the management of the road system in general (TRH4, 1996). For the efficient application of a life cycle approach by road authorities, technical issues (i.e. demands), such as the actual traffic loading patterns of especially heavy vehicles, as well as the effects of different tyre types and inflation pressures should be known and be as accurate as possible.

In a recent study it was estimated that the *average* (median) tyre inflation pressure of heavy vehicles (axle mass > 7 000 kg) in the province of Gauteng (the economic centre of South Africa) had increased by approximately 18 per cent over the last 20 years, from 620 kPa to 733 kPa (De Beer, 1995). See Figure 1a. The maximum inflation pressures had also exceeded 1 000 kPa. Further analysis of the results in Figure 1a indicated that the second peak at approximately 800 kPa represents the average inflation pressure for trucks with five (5) or more axles. During the last two decades there has also been a change from bias/cross-ply truck tyres to radial tyres in South Africa. See Figure 1b. Approximately 86 per cent of current truck tyres are of the radial type, the remaining tyres being of the bias or cross-ply type. Figure 1b also indicates the distribution of some of the more widely used radial tyre types in South Africa. The use of wide base ("Super Single") tyres is limited to approximately 4 per cent in South Africa, but is expected to increase as a result of a recent increase in world trade, as mentioned above, and a recent increase in the legal axle load limit during 1996 in South Africa (South Africa, 1996).

Observations of road surface behaviour. Over the years in South Africa, large-scale use has been made of relatively thin (< 50 mm) asphaltic concrete surfacing layers on flexible pavements supported by high quality crushed or natural gravel bases. Much use has also been made of lightly cementitious materials as part of the main structural (i.e. base and subbase) layers. This resulted in the so-called "inverted" or "upside down" pavement structures which have served the country well over the last two decades. Most of these pavements, however, are now nearing the end of their structural design life, most *without* bearing capacity problems, per se. The problems associated with most of the national highways and paved provincial roads are related to surfacing problems like surface cracking, potholes, surface crushing failures, permanent deformation within the asphaltic concrete surfacing layers, ravelling, bleeding, crocodile cracking of surfacing chip seals, etc. More than a decade of experience on real roads using Accelerated Pavement Testing (APT) technology with the Heavy Vehicle Simulator (HVS) in South Africa (Freeme et al, 1981, 1982, 1987, De Beer et al, 1988, De Beer 1991, Horak et al, 1992) has demonstrated that most of the traffic-associated failures result from the top down, and not from a lack of subgrade support (i.e. subgrade bearing capacity). This finding caused, amongst other things, some research activity to be focussed on the effect of actual *tyre/pavement contact stresses* acting at the tyre/pavement interface. It is firmly believed that most of the observations and the results of APT research in South Africa indicate that the damage is caused not only by the cumulative legal loading and overloading of heavy vehicles, but also by the *load intensity* (i.e. effective contact stresses) acting at the tyre/pavement interface. To study these forces (i.e. contact stresses) at the tyre/pavement interface, a rather unique system has been developed in South Africa. The system is officially referred to as the **Vehicle-Road Surface Pressure Transducer Array (VRSPTA),** end was developed to measure contact stresses under moving pneumatic wheel loads effectively.

The scope of this paper is, *firstly*, to discuss the development, calibration and use of the VRSPTA system, and *secondly*, to discuss some analyses and basic implications of the test results. Some effects of non-linear contact stresses on pavements incorporating thin (< 50 mm) asphalt surfacing layers are also discussed.

BACKGROUND

The use of relatively thin (< 50 mm) surfacing layers in asphalt pavements is becoming more popular for the construction of new pavements and the rehabilitation of road networks in South Africa. However, appropriate mechanistic pavement design techniques for thin asphalt surfacing layers are lacking, primarily because of the inappropriate definition of the contact stress condition at the tyre/pavement interface. Usually, a circular area with a uniform distribution of only the vertical contact stress is used for design purposes (Yoder et al, 1975). The question of the tyre/pavement load/stress idealization, however, is not new, since much work has been done in the past for improved definition thereof. (Bonse et al, 1959; Freitag et al, 1962; Wardle, 1977; Uzan et al, 1987; Van Vuuren, 1974; Tielking, 1984; 1987; Woodside, 1992; Woodside et al, 1992; Jacobs et al, 1992; Mante et al, 1995a, 1995b).

The research discussed in this paper includes a description of the research undertaken in South Africa into the determination (measurement) of the ***three-dimensional tyre/pavement contact stresses under slow moving wheel loads***. A research programme was started in 1992 through which a system for the improved quantification of the three-dimensional (3-D) tyre/pavement contact stresses was successfully developed. The concept "Stress-In-Motion" (SIM), however, is not new, since many earlier attempts were made for such measurements. A wide range of systems was used, varying from single instrumented pin systems in road surfaces to laboratory equipment (Martin, 1936; Bonse et al, 1952; Freitag et al 1962; Lister et al, 1968; Davisson 1969; Lippmann et al, 1974; Clark, 1981; Roberts et el, 1985; Marshek et al, 1986; Cunagin et al, 1986; Pezo et al, 1989; Sebaaly et al, 1989; Huhtala, 1990).

GENERAL CHARACTERISTICS OF THE VEHICLE-ROAD PRESSURE TRANSDUCER ARRAY (VRSPTA) SYSTEM

The Vehicle-Road Surface Pressure Transducer Array (VRSPTA) system discussed here consists mainly of an array of triaxial strain gauged steel pins fixed to a steel base plate, together with additional non-instrumented supporting pins, fixed flush with the road surface. The data acquisition system used in this study allows for the simultaneous recording of 63 channels (strain gauges) up to a sampling rate of 12 kHz per channel. The system is automatically triggered by a moving wheel and is designed to measure at wheel speeds from 0,3 m/s (1 km/h) up to 7 m/s (25 km/h), and vertical loads up to 200 kN (horizontal loads up to 20 kN). A schematic layout of the VRSPTA systems applied in this study is given in Figure 2 below, as well as in Plate 1.

Basically, the VRSPTA is installed flush with the surface of the pavement to a relatively high level of precision within a few millimetres. This is needed to minimize measured load variation as a result of dynamic impact on the system at relatively high wheel speeds. See also Plate 1 where several images of the VRSPTA in operation under the HVS are illustrated.

The VRSPTA system discussed here is the second prototype system (i.e SIM MK II), which incorporates some improvements relative to the first system developed during 1992/3 (i.e SIM MK I) (De Beer, 1994). SIM MK I was developed to *prove the concept* of the measurements of the 3-D stress components at the moving tyre/pavement interface. Subsequent systems were develop primarily for the purpose of the development of tyre/pavement contact stress data basis for pavement design and evaluation.

The stresses measured simultaneously with the VRSPTA, and the convention used in this paper are given below(see also Figure 2):

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

As was reported earlier, SIM MK I manifested some inaccuracies of up to 25 per cent of the total load measured after integration of the vertical stress volume (De Beer, 1994), but this was corrected with improvements to the design of the SIM MK II VRSPTA system used for the measurements given in this paper (De Beer 1995b, 1995c, De Beer et al, 1996).

Friction of the surface of the VRSPTA. Since it is critical to ensure an adequate amount of friction between the tyre and the surface of the VRSPTA to obtain an effective transfer of especially the horizontal forces (i.e. transverse (or lateral) and longitudinal), it was necessary to design the surface of the VRSPTA to match a surface, equivalent in friction to an "average" asphaltic concrete or surfacing material used on pavements. It was also necessary that the full tyre/pavement contact patch (area) be supported by the same stiffness or rigidity as those areas where the actual measurements are recorded (i.e. instrumented pins) during the movement of the wheel across the surface of the VRSPTA.

Based on the general dimensions of aggregate used for asphaltic surfacings in South Africa, which range from 6 mm to 19 mm, the majority being around 13 mm, and taking into account that these aggregates do not consist of flat planes on the surface should it was decided that the diameter of the pins on the VRSPTA surface to be approximately 9.7 mm, spaced at 17 mm from centre to centre. Another consideration was the spacing of tread grooves on typical on-road truck tyres which varies from 20 mm to 60 mm. The arrangement of the pins at 17 mm intervals was chosen to cover as much of the area as practically possible to give in an adequate definition of the contact stresses using only one coverage of typical truck tyres. The surface friction characteristics of the VRSPTA were tested at an earlier date (De Beer, 1995b) with the TRL (Transport Research Laboratory, UK) Pendulum Skid Resistance Tester, in accordance with Road Note 27 (1960). In dry conditions it gave a skid resistance value of 76 (mean of 15 values, s = 1.1). In wet conditions the skid resistance was 37 (n = 10, s = 4.7). The value of 37 relates to a "potentially slippery" road (values < 45), according to RN 27. The measured value of 76 during dry conditions on the surface of the VRSPTA relates to an equivalent road surface with a "good" skid resistance ..."fulfilling the requirements even of fast traffic, and making it most unlikely that the road will be the scene of repeated skidding accidents" (RN 27, 1960). It should be mentioned that RN 27 requires the skid resistance testing to be done in "wet", i.e. the most unfavourable, conditions. As measurements with the VRSPTA are done in dry conditions, however, it can be argued that the friction between the rubber tyre and the VRSPTA steel surface is relatively high. This represents a condition where the horizontal forces between tyre and VRSPTA can be considered as relatively close to the expected maximum forces (hence maximum stresses). It is therefore unlikely that in practice these stresses will be *underestimated* by the current

VRSPTA system.

However, it is acknowledged that the *effective friction* between the test tyre and the VRSPTA surface has a dominant effect on the magnitude of especially the horizontal forces but, as stated, the current VRSPTA surface represents an "average equivalent dry road surface" according to the Pendulum test and is assumed to be acceptable for the purposes of this study.

Further research work, however, should also concentrate on varying the *effective surface friction* conditions of the VRSPTA, but this is outside the scope of this study.

Stiffness and calibration of the VRSPTA. Since the principle of measurement of the VRSPTA is based on strain gauge technology, calibrating each of the instrumented pins in three (3) directions (i.e. 3 dimensional or triaxial load cells or sensors), the real stiffnesses in the three measuring directions of the instrumented pins do not directly influence the results, as long as the sensitivity of measurement is large enough to obtain useful voltage output readings. In order to provide the pins with a more sensitive top area, a conical shape was preferred. In addition, the pins were hollowed out to increase this sensitivity. This resulted in a hollow conical-shaped pin, with diameters of 16 mm and 9.7 mm for the bottom and top respectively. In addition to the hole in each pin, four windows at 90 degree spacings were included near the top to further increase the sensitivity at the top of each pin. It is, however, important that the loaded wheel should be fully supported by the same "stiffness" (or rigidity) when the measurement is made, so that the tyre contact patch is not distorted as a result of non-uniform support. Therefore all the pins on the VRSPTA (1041 in this case) have exactly the same shape, stiffness, contact area, sensitivity to loading, fixing and bending characteristics.

Each of the instrumented pins (sensors) is independently calibrated using a high precision miniature load cell (± 1 per cent of full scale, i.e. 1 per cent x 500 Newton = 5 Newton, according to the manufacturer's calibration report). A separate calibration frame is installed on top of the VRSPTA system and calibration for each of the three directions of each instrumented pin is done from zero load to a safe maximum recommended load of approximately 500 Newton. This is repeated several times to provide for a linear fit between the voltage output and the load reading from the high precision load cell during the calibration. This linear fit is obtained for each of the total 63 directions of the VRSPTA and then used in the software to convert the voltage output to load. Figure 3 indicates a typical result of one of the 63 calibrations done on the VRSPTA. It was found that the *systematic error* associated with this calibration method varies between 2 per cent at 80 per cent prediction confidence limit, and 10 per cent at a 99 per cent prediction confidence limit (De Beer et al, 1996).

Accuracy of the VRSPTA system. The accuracy *(i.e. systematic and random errors*) associated with the current VRSPTA system, regarding the truthful registration of the contact stresses between the tyre and the pavement surface, is mainly determined by the following factors:

i) the accuracy of the conversion of the force calculated from the voltage output of the measuring pins, and then the calculation of the stresses by dividing the calculated forces by a constant *effective area*. The initial conversion from voltage to load contains a certain *systematic error* with respect to the linear fit obtained in the laboratory, as well as to the spread of the data around the regression function. The effective diamond-shaped area applied during post-processing to convert the measured three load components to *the three average contact stress* components over that area is illustrated in Figure 4.

ii) the accuracy of the simulation of what actually happens at the interface between the tyre and the actual pavement, as the surface of the VRSPTA is not what pavements are usually made of. In this case the *effective friction* is regarded as the dominant factor. This is the second source of a systematic error from the VRSPTA.

(iii) the existence of *random errors* due to the non-laboratory conditions under which the current system operates in the field (also under the HVS). As far as "accuracy" of the VRSPTA is concerned, it depends on the confidence level (or intervals) selected to describe the variation of the laboratory data (from the instrumented pins) around the average relationship between the load and voltage output.

With the field testing done to date, it was found that the *random error* of the VRSPTA system relating to the measurement of total load, and also to that of maximum contact stresses is generally less than 10 per cent (De Beer et al, 1996).

Figure 5 show a typical random error in total load measurement found during a recent study on a wide-base single tyre with the VRSPTA (De Beer et al, 1996).

TYRE/PAVEMENT CONTACT STRESSES MEASURED WITH THE VRSPTA

Since the development of the first prototype VRSPTA system in 1994 (i.e SIM MK I), several studies regarding the tyre/pavement interface contact stresses have been done on a research basis (De Beer, 1994; De Beer, 1995b, 1995c; De Beer et al, 1996). These studies include the investigation of several types of truck tyres, such as bias/cross-ply tyres used on the HVS and radial tyres, including some wide-base singles. Limited testing was recently done on a light commercial vehicle and trailer at speeds ranging from 5 km/h up to 60 km/h. In Table 1 below a description of the various types of tyres tested to date is given. Only the most important characteristics of the 3-D contact stresses found from using these tyres will be discussed here.

Basic three-dimensional (3-D) contact stresses under a smooth tyre. During the 1994 study (De Beer, 1994) some basic contact stress distributions for a smooth free-rolling, loaded bias-ply truck tyre (Reference Number I, i.e. tyre Type I , Table 1) were identified. This research prompted further interest in the actual stress distributions under real truck tyres, as well as the investigation of possible differences in contact stress definitions between tyre types. Some of the basic contact stress distributions found during 1994 are illustrated in Figure 6. The figure indicates the three basic stress distributions found under a free-rolling single smooth bias/cross-ply tyre, namely:

- Vertical contact stress;
- Transverse (or lateral) stress, and the
- Longitudinal stress distributions.

Vertical contact stress: Based on the design layout of the VRSPTA, load/stress recordings are obtained every 17 mm across the tyre contact patch. Therefore a typical patch width of 230 mm will result in 13 load recordings from thirteen instrumented pins from the VRSPTA during one single passage of a load. See Plate 1 and Figure 6. The system used here (SIM MK II) is 315 mm wide. Typically, for slow moving, free-rolling tyres, the vertical load on each instrumented pin increases to a maximum and then decreases. For the smooth tyre it was demonstrated that the maximum vertical contact stress changed from the tyre centre towards the tyre edges when the tyre was heavily loaded and/or under inflated. Compare Figures 6A and 6D. Also for slow-moving, free-rolling tyres, the stress distribution in the direction of travel is parabolic for relatively lower loads and tends to flatten out for the higher loads.

Transverse (or Lateral) contact stress. The stress distribution found for the transverse direction at right angles to the direction of travel for a free-rolling smooth tyre clearly indicated *inward shear* towards the tyre centre and these stresses are in balance, with zero stress at the tyre centre. See Figures 6B and 6E. Therefore the resultant force is zero. From this it may be postulated that the pavement surface is experiencing a tensile stress *outside* the tyre edge and a state of compression towards the tyre centre. This has also been suggested by others (Wardle, 1977; Jacobs et al, 1992; Mante et al, 1995a, 1995b). For heavily loaded tyres, the transverse stress also increases (Figure 6E). With limited testing in a mode of sideways shear using the HVS, it was found that the transverse stress *increases* towards the one side at maximum shear. In this condition the difference in transverse shear stress equals the *additional* shear stress, owing to sideways shear or, more correctly, to “cornering” of a tyre at a curve.

Longitudinal contact stress. The measured longitudinal contact stresses in the direction of travel are indicated in Figures 6C and 6F. For free-rolling tyres these stresses are the lowest of the three stresses and normally result in two or three peaks. These peaks occur near the fore and aft positions of the tyre and are highly dependent on the rolling resistance between the tyre and the road and on the traction, braking or acceleration imposed on the tyre. In the case of heavy overloading, stress reversals within the contact patch are possible, resulting in some peak stress (in this case three) concentrations, as indicated in Figure 6F. In general these measurements agree fairly well with those predicted by theory and by other experimental data (Clark, 1981; Tielking et al, 1987, 1994; Lippmann et al, 1974).

Basic relationships between tyre inflation pressure and contact stress of the smooth tyre. In order to understand the tyre/pavement interface stresses better it is worthwhile to study some basics first. Several methods exist, and have been used in the past, to quantify the vertical contact stress between a tyre and the road surface. Most of these are based on the rather simplistic approach of measuring the contact area using the tyre imprint and dividing the measured vertical load by this area to obtain the average vertical contact stress.

TABLE 1. SUMMARY OF TYPES OF TYRES TESTED WITH THE VRSPTA (SIM MK II) IN THIS STUDY

TYRE TYPE	REF. NUMBER (TYRE TYPE)	TYRE MAKE	ORIGIN	TREAD PATTERN AND TEST CONDITION	LOAD RANGE (kN)	INFLATIO N PRESSURE RANGE (kPa)
11.00 X 20, 14 ply, bias/cross-ply rating	I	Goodyear	HVS, South Africa	Smooth*, single tyre on HVS (June 1994)	20-50	420-720
11.00 x 20, 14 ply, bias/cross-ply rating	II	Goodyear	HVS, South Africa	Used dual tyres on HVS (February 1995)	10 - 40	420-720
46 x 16, 30 ply rating, 225 mph (Aircraft tyre)	III	SP44, Goodyear	Aircraft tyre on HVS	Used, not smooth, single on HVS (June 1994)	20-50	1448
315/80 R 22.5	IV	Michelin	HVS, South Africa	New, single on HVS (July 1996)	20-100	500-1 000
425/65 R 22.5 (Wide Base)	V	Michelin	HVS, South Africa	New, single on HVS (July 1996)	25-100	500-1 100
425/65 R 22.5 R160AZ (Wide Base)	VI	Bridgestone	LINTRACK, The Netherlands	Used, single on HVS, then buffed twice and re-tested. (June 1996)	25-100	500-1 100
425/65 R 22.5 R164BZ (Wide base)	VII	Bridgestone	LINTRACK, The Netherlands	New, single on HVS (June 1996)	25-100	500-1 100

* Some of the tyres tested were smooth (buffed down or trimmed) to a relatively smooth surface. This was to minimize scatter owing to the tread pattern in the results to establish some basic contact stress distributions.

This method has several shortcomings: firstly, in that only "average" stress is obtained, as it is assumed that the stress is evenly distributed over the contact area. Secondly, the tyre tread pattern is not always considered in such an analysis. This, however, can be taken into account by reducing the total area measured to the effective area by subtracting those areas of zero contact inside the tyre print before the stress is calculated (Van Vuuren, 1974; Lister et al, 1968). Nevertheless, this method was applied widely, and most pavement design methods today are based on the assumption of "average" or uniformly distributed vertical stress, which equals the tyre inflation pressure. This approach may be adequate for the design and analysis of relatively thick (>100 mm) asphalt surfacing and base layers but in the case of relatively thin surfacings, as discussed here, this assumption needs more validation. In order to study the vertical contact stress distribution of the smooth tyre and the associated relationship(s) with inflation pressure and load, several tests were done with the VRSPTA, where the wheel load was increased at constant inflation pressure, and also where the tyre inflation pressure was increased under constant load conditions. In this case the loads on the single smooth tyre varied between 20 kN and 50 kN, and the inflation pressure from 420 kPa to 720 kPa. For simplicity, the measured vertical contact stress test results are shown graphically in Figure 7. The layout of the figure is designed to enable the different load/inflation pressure cases to be compared, starting from the lower left corner with the lowest load (20 kN) and lowest inflation pressure (420 kPa) conditions. Then, by moving upwards, the figure represents an increase in load for all cases, while moving across the figure to the right represents the increase in tyre inflation pressure. The figure clearly demonstrates that an increase in load results in an increase in the contact stresses at the tyre edges, while an increase in inflation pressure results in an increase in the contact stress at the tyre centre. Therefore it is obvious that the tyre/pavement contact stress includes both the inflation pressure and the tyre loading. It is, however, accepted that the load/inflation pressure conditions given here are not confined to those prescribed by the tyre manufacturer for normal operational use. The purpose of Figure 7 is to convey a rather important message concerning the basic problem of tyre/pavement interface stress conditions under normal loading as well as overload/under-inflation cases. The dependence of contact stress on both tyre load and inflation pressure is therefore indicated. An analysis of the distribution of vertical contact stresses (De Beer, 1995b) indicated that the vertical stresses on the smooth tyre are not normally distributed under the smooth tyre, and tend to be biased towards the higher stress at lower loads. However, a more normal distribution is obtained under higher loads. See the bar charts in Figures 8 and 9.

Quantification of the vertical contact stresses. In order to study the simplistic approach discussed earlier of dividing the tyre load by the imprint area, the results of the smooth tyre discussed above were used and compared with results based on the same assumption that was made in South Africa during 1974 for the mechanistic design of pavements in South Africa. Van Vuuren (1974) suggested that the average vertical contact stress for truck tyres is *lower* than the inflation pressure and is obtained from the equation below:

$$q = 0.61p + 145 \quad \text{.......................................} \textbf{\textit{Eq 1}}$$

where:

q = Average vertical contact stress (kPa),
p = Tyre inflation pressure (kPa).

For the smooth tyre it was found that the method above suggested by Van Vuuren *underestimates* the actual vertical stress. In the light of the non-normal distribution of vertical stresses (Figure 8), it is suggested that a percentile based approach should rather be used to obtain the contact stresses needed for design purposes (De Beer, 1995a). As an indication of this approach, the results of the smooth tyre were used and compared to those of Van Vuuren (1974), and are illustrated in Figure 10. The figure clearly demonstrates the underestimation of contact stresses by Van Vuuren (1974) (indicated by the solid line in Figure 10). If the average tyre inflation pressure (620 kPa) for heavy vehicles obtained in 1974 is used in Eq 1, the uniform vertical design contact stress of 520 kPa is obtained, which was the basic stress idealization used until now in the South African Mechanistic Design Method (Theyse et al, 1996).

The results of the smooth-bias/cross-ply tyre were then converted into the same format as that of Eq 1. At the rated tyre load and inflation pressure of this tyre the maximum measured contact stresses measured with the VRSPTA exceed the inflation pressure by approximately 29 to 58 per cent. Because of the lack of any other direct relationships between tyre inflation pressure and contact stress, it is recommended (at least for HVS research and mechanistic design in South Africa) that the 1974 - Eq 1 should rather *not* be used. Instead, the newly developed relationships (including only the inflation pressure[1]) for bias/cross-ply tyres given below in Table 2 at different percentile design values are recommended for use *if the tyre load is not known*.

The design percentile approach suggested here ties in well with a similar approach towards the structural design reliability for pavements in South Africa suggested by Theyse et al (1996).

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[1] The dependence of the three-dimensional (3-D) tyre/pavement contact stresses on BOTH the *inflation pressure* and the *tyre load* for several types of tyres is discussed in detail later.

TABLE 2: SUGGESTED INTERIM DESIGN RELATIONSHIPS BETWEEN TYRE INFLATION PRESSURE AND VERTICAL TYRE CONTACT STRESSES AT DIFFERENT DESIGN PERCENTILE VALUES.

DESIGN PERCENTILE (%)	A*	B kPa	DESIGN CONTACT STRESS** (kPa)
50	0.730	174	700
80	0.690	296	800
90	0.723	310	840
95	0.746	311	860
Van Vuuren (1974)	0.61	145	590
Maximum	0.833	312	920

* $q = \boldsymbol{A}p + \boldsymbol{B}$, with inflation pressure, $\boldsymbol{p}$, in kPa, $\boldsymbol{q}$ = design contact stress.

** This design vertical contact stress applies to the average inflation pressure of 733 kPa recently found for South African heavy vehicle traffic (De Beer, 1995a) (See also Figure 1).

Table 2 also indicates that the higher the design percentile value, the higher the vertical contact stress to be used for pavement design purposes, as expected.

Tyre centre vs tyre edge vertical contact stresses. The VRSPTA tests with the smooth tyre clearly indicated that the higher the load, the higher the vertical contact stresses *at the tyre edge*. This condition has been demonstrated experimentally by various researchers, and postulated from a purely theoretical approach (Bonse et al, 1962; Davisson, 1969; Clark, 1981; Tielking, et al, 1987; Yap, 1988; Hansen et al, 1989; Huhtala, 1990). This aspect was also investigated further for the smooth tyre studied here, and some results are illustrated in Figures 11 to 14. Figures 11 and 12 represent the case where the load was kept constant, and the inflation pressure varied from 420 kPa to 720 kPa. Two load levels are shown here, namely 18 kN (Figure 11) and 48 kN (Figure 12). Both figures illustrate that the greatest influence on the development of contact stress is towards the tyre centre and is primarily controlled by the tyre inflation pressure. It is also evident from these figures that the average stress over the tyre centre (i.e. VRSPTA pin 7 to pin 16 on Figure 11, and pin 6 to 17 on Figure 12) is *higher* than the associated inflation pressure. During extremely high loading some effects of tyre pressure on the tyre edge contact stresses are noted, possibly owing to the greater deflection and bulging of the tyre, which causes an additional inflation pressure effect towards the tyre edge and also as a result of reduced tyre volume. See Figure 12. Figures 13 and 14 show the maximum developed vertical contact stresses at constant tyre inflation pressure, but with a varying tyre load. Figure 13 illustrates the case of an inflation pressure of 420 kPa, where the load varied between 20 kN and 50 kN. Figure 14 illustrates the case in which the inflation pressure was 620 kPa, and the load varied from 20 kN to 50 kN. Both figures indicate clearly that the tyre loading studied here did not affect the development of vertical contact stresses towards the tyre centre but strongly influenced the development of vertical contact stresses at both the tyre edges. It should also be noted that the cases given in Figures 13 and 14 represent, in principle, more of the "reality", since it is more likely that the tyre load will change on a moving vehicle as a direct result of vehicle load, and not because of a change in the tyre pressure. In addition, the development of dynamic loading due to vehicle/tyre movement and irregularities on the road surface will also cause a variation in tyre load more than the tyre inflation pressure. It is therefore evident that relative overloading and *under inflation* will cause relatively high tyre edge contact stresses. The vertical stresses at the tyre edges could *exceed* the inflation pressure by a factor of two to three. This will be discussed in more detail later. For general design purposes of especially thin asphalt surfacings, it could be argued that it is important to differentiate between these two types of contact stress developments across the tyre width, since *overloading* is generally considered a serious problem in South Africa. Recent statistics indicate that 44 per cent of the 52 350 heavy vehicles weighed in South Africa during 1995 were overloaded, of which 26 per cent were charged (Sallie, et al, 1995, Nordengen et al, 1995). It may therefore be that the position of the maximum vertical contact stresses of overloaded heavy vehicles in South Africa is at the tyre edges. If the damage to road surfacings due to these vehicles is to be estimated, the correct magnitude of these stresses and of their distribution across the width of the tyre need to be known. For this purpose two *interim* design relationships were developed from the studies on the smooth tyre. The two cases are, *firstly*, the vertical contact stress at tyre centre, and *secondly,* the vertical contact stresses at both the tyre edges:

Estimation of the vertical contact stress at tyre centre. From Figures 11 to 14 it is clear that the vertical tyre/pavement contact stresses at the inner portion of the tyre width are primarily controlled by the tyre *inflation pressure*. In this case the inner 60 per cent of the tyre width was selected over which the relationship between tyre inflation pressure and measured contact stress was developed. The found relationship is given in Eq 2 below:

$$q_{60} = 0.86p + 175 \quad \text{...Eq 2}$$

where:

q_{60} = Average vertical contact stress at tyre centre area in kPa;

p = tyre inflation pressure in kPa over a range of 420 kPa to 720 kPa, and a single tyre load range from 20 kN to 50 kN.

$r^2 = 0.98$

Standard Error in q_{60} = 20 kPa

Estimation of vertical contact stress at the tyre edges. In this case the contact stresses are predominantly controlled by the *tyre loading*, and the relationship between tyre load and edge contact stress is given in Eq 3.

$$q_e = -0.53L^2+57.46L- 534.05 \quad \text{......................Eq 3}$$

where:

q_e = Vertical Contact Stress at the tyre edges in kPa.

L = Tyre load in kN, ranging between 20 kN and 50 kN.

$r^2 = 0.97$

Standard error in q_e= 54 kPa.

Ratios of maximum stresses found for the smooth tyre. Analysis of the ***ratio of the maximum (peak) contact stress*** values between the measured stresses in the three directions: Vertical (Z), Transverse (Y), Longitudinal (X) of the free-rolling smooth tyre measured on the new VRSPTA system (SIM MK II) resulted in the following: **10 : 3.6 : 1.4.** This ratio was similar to an earlier finding on the same tyre, but with the previous VRSPTA system, SIM MK I (De Beer, 1994). It is therefore suggested that if studies need to be done on relatively smooth (worn out) bias/cross-ply tyres based on all three stress components, the ratio as given above be used. It should, however, be remembered that the effect of sideways shear (or cornering) is *not* included in the above ratio, and in such cases it may be advisable to increase the transverse stress ratio value from 3.6 to 4.5 or in extreme cases to 5, as it was found (with VRSPTA testing) that sideways shear results in *additional* transverse shear forces. More discussion follows later on sideways shear measured by the VRSPTA, on tyres with tread grooves.

Conclusions on the smooth tyre results. The test results from the smooth tyre assisted in the improved understanding of some of the most basic tyre/pavement contact stress distributions under pneumatic truck tyres. The interdependency of the inflation pressure and tyre load was also clearly illustrated. Although the tyre studied in this section was of the bias/cross-ply type (of which many were used in South Africa up to the early 1980's), it nevertheless, provided some basic insight previously not generally available to pavement engineers in practice.

Tests on tyres with tread grooves. Several tyres with tread grooves were also tested with the VRSPTA, and a summary of the test results is given in the following sections. Table 1 gives a summary of seven (7) types of tyres tested and discussed here. Most of the VRSPTA tests were done at slow speed (0.31 m/s to 0.34 m/s), in the free-rolling mode under the HVS04. Limited testing was done in the sideways shear mode. Discussions of the tests on the different tyres from Table 1 follow in the next sections, with a more detailed discussion on the results of a typical bias/cross-ply tyre (Type II) used previously in South Africa.

Tyre Ref Number II (Table 1). This type of tyre represents the normal truck tyres which were used for more than 20 years in the South African Heavy Vehicle Simulator (HVS) testing. The tyre is a 11.00 x 20 14 bias/cross-ply tyre and normally a set of dual wheels are used for normal accelerated pavement testing (APT) (HVS testing, Freeme et al, 1981, 1982, 1987, Horak et al, 1992, Steyn 1995).

Practice to "simulate" relative damage using Accelerated Pavement Testing (APT) facilities such as the HVS. Before the actual contact stress measurements for this tyre are discussed, it is important to be familiar with the general widely accepted concept of *relative damage* and its simulation by accelerated pavement testing facilities such as the HVS. It was (and still is!) accepted that in order to accelerate the operational efficiency (i.e maximize the number of load/stress cycles in relatively short periods of time) of the HVS or other similar traffic load simulation systems, like the Accelerated Loading Facility (ALF) (Jameson et al, 1996); Mobile Load Simulator (MLS) (Hugo, 1996); Circular test track at Nantes in France (LCPC), LINTRACK at Delft in the Netherlands- (Groenendijk et al, 1994, 1996a, 1996b); CAPTIF in New Zealand (Pidwerbesky, 1989, Pidwerbesky et al, 1990a, 1990b); etc, the test wheel load has to be increased, often without an associated increase in tyre inflation pressure. Usually, the "4th power law" for relative damage and "equivalency of loads" is then assumed to study the effects of different loads on pavement damage (Irick et al, 1964, Sebaaly et al, 1992, Ioannides et al, 1993). By using this method the number of "equivalent load applications" of a certain base load, P_b, is obtained by raising the ratio of the test load P and some base load, P_b, to the 4th power, i.e. $(P/P_b)^4$. This method is based on the assumption of "equivalent load equivalent damage", which may not always be true. For relatively high loads, P, this might have a large influence on the effective load (or stress) cycles actually applied to the test pavement. For example, an increase of a test load P to 70 kN, were the legal load P_b = 40 kN, results in an "equivalent" number of load applications of $(7/4)^4$ = 9.4 times the legal load per single application of the 70 kN load. This may be acceptable for certain relatively thick surfacing layers (> 100 mm) and relatively strong pavements, but owing to the actual contact stress distributions resulting from this type of load increase, it may be incorrect for use on pavement structures with thin surfacings. This, however, will be discussed later in more detail, based on actual measured contact stresses.

Basic Contact Stress Distributions on the HVS bias/cross-ply tyres *with* tread grooves. As may be expected, because of the tread patterns on most truck tyres, the tyre/pavement contact stresses will be highly variable, and in almost all cases, it may be zero at a position *between* the tread grooves. Some basic measured distributions on the tyre Type I (Ref I, Table 1) are illustrated in Figure 15. The figure indicates digital images of all three basic stresses, i.e. vertical, transverse and longitudinal directions. It is clear that these stresses are highly variable compared to those found for the smooth tyre (Compare Figure 15 with Figures 6, 7 and 11 to 14) . For the vertical stress it is also clear that for relatively low loads the maximum stress occurs at the tyre centre rib, and at higher loads the maximum stresses move towards the tyre edge ribs (similar to what was found for the smooth tyre). The transverse stresses seem to indicate basic *outward* shear on some pins and some *inward* shear on others. This, however, is to be expected, since some pins on the VRSPTA are fully loaded with a resultant transverse force in one direction or the other, and some pins will be partially loaded in one direction or the other. Although this, in itself, is a function of the layout of the pins in the VRSPTA, the authors believe that it is closer to what is expected to happen on relatively rough surfaces where the asperities of the individual aggregates penetrate the surface of the tyre in the contact patch. The longitudinal stress seems to be the least affected by the tyre tread pattern, and each of the ribs acts like a "smooth tyre" in itself. This is also believed to be the case for the VRSPTA-measured transverse stresses. Figure 15 also shows cross sections of the vertical measured contact stress, and it is clear that between ribs, relatively low stresses are measured, and in some cases zero stress, as might be expected. Figures 16 and 17 illustrate the effect of inflation pressure and load on this tyre, again similar to those found on the smooth tyre, where the inflation pressure predominantly controls the contact stress at the tyre centre (Figure 16), and the load controls the contact stresses at the tyre edges (Figure 17).

Analysis of maximum stresses for bias/cross-ply tyres with tread grooves used on the HVS. Analysis of the vertical contact stress distribution of this tyre type (Ref I, Table 1) indicated that the vertical stress is also not uniformly distributed about the mean, and is much more irregular than that obtained for the smooth tyre. Figure 18 illustrates this in a bar chart (similar to Figures 8 and 9), for the bias/cross-ply HVS tyre at 420 kPa and a load of 17 kN. Figure 19 indicates the percentage cumulative frequency of the vertical contact stress for a range of loading from 14 kN to 40 kN, at an inflation pressure of 520 kPa. From Figure 19 an estimate of the percentile stresses associated with this condition of loading and inflation pressure is obtained. It should be pointed out that the HVS tyre load and inflation pressure rating is from 18 kN at 420 kPa to 26 kN at 730 kPa (SABS 1550, Table 7, 1992).

Table 3. Percentile vertical contact stresses found for the HVS tyre (load range 14 kN to 40 kN) at 520 kPa inflation pressure(see also Figure 19)

DESIGN PERCENTILE (%)	RANGE OF VERTICAL CONTACT STRESS (kPa)	
	Normal Load: 14 to 21 kN (Stress at tyre centre)	50 % to 100 % Overloading (Stress at tyre edges)
50	620 - 700	820 - 900
80	780 - 950	1 050 - 1 100
90	950 - 1 000	1 075 - 1 250
95	970 - 1000	1 150 - 1 300
Max	980 - 1000	1 190 - 1320

The percentile stresses for this case at various loading conditions are given in Table 3. When the tyre is not overloaded, these stresses occur close to the centre ribs of the tyre. The stresses obtained under extreme overloading conditions (approximately 50 per cent up to 100 per cent overloading) are also given in this table. The stresses given are an indication of the *actual contact stresses* (in this case mainly tyre edge stresses) when the loading on accelerated pavement test facilities such as the HVS is arbitrarily increased to higher loads at the same tyre inflation pressure (i.e. 520 kPa on the HVS). The above procedure is normally done to achieve "accelerated" test conditions, as discussed earlier, and clearly indicates possible errors in assumed contact stress values during analyses of the results from these test systems. In the case discussed here, the increase in actual contact stresses

TABLE 4. SUMMARY OF THE MAXIMUM 3-D (X,Y,Z) STRESSES MEASURED WITH THE VRSPTA ON THE TYRES DEFINED IN TABLE 1.

TYRE TYPE	REF No.	TYRE LOAD RANGE (kN)	INFLATION PRESSURE RANGE (kPa)	RANGES OF MEASURED MAXIMUM CONTACT STRESSES (kPa), AND NORMALIZED CONTACT PRESSURE (NCP)*						RATIO OF AVERAGE MAXIMUM STRESSES			COMMENTS
				VERTICAL (Z)	NCP	TRANSE-VERSE (Y)	NCP	LONGI-TUDINAL (X)	NCP	Z	Y	X	
11.00 X 20, 14 ply (bias/cross)	I	20-50	420-720	662 - 1 424	1.6-2.0	230 - 470	0.5-0.6	97 - 438	0.2-0.6	10	3.60	1.40	Smooth tyre ** Free rolling
11.00 x 20, 14 ply (bias/cross)	II	10-40	420-720	952 - 1 501	2.0-2.1	117 - 408	0.3-0.6	41 - 248	0.1-0.3	10	2.10	1.65	Free rolling
46 x 16, 30 ply (Aircraft)	III	20-50	1448	2 057 - 2 240	1.4-1.5	261 - 502	0.2-0.3	137 - 279	0.1-0.2	10	1.70	1.00	Free rolling
315/80 R 22.5	IV	25-100	500-1 000	900 - 2 689	1.8-2.7	59 - 410	0.1-0.4	99 - 538	0.2-0.5	10	1.82	1.53	Free rolling
		75	900	2 381	2.6	637	0.7	302	0.3	10	2.68	1.27	Shear mode***
425/65 R 22.5 (Wide Base)	V	25-100	500-1 100	978 - 2 204	2.0-2.2	58 - 388	0.1-0.4	53 - 316	0.1-0.3	10	1.75	1.43	Free rolling
		75	950	2 048	2.2	579	0.7	264	0.28	10	2.80	1.30	Shear mode
425/65 R 22.5 R160AZ (Wide Base)	VI	25-100	500-1 100	970 - 1 837	1.9-1.7	91 - 354	0.2-0.3	53 - 386	0.1-0.4	10	1.52	1.15	Free rolling
				791 - 1 827	1.6-1.7	132 - 250	0.3-0.2	127 - 390	0.25-0.4	10	1.12	1.11	Free rolling(Smooth)
425/65 R 22.5 R164BZ (Wide base)	VII	25-100	500-1 100	917 - 2 183	1.8-2.0	90 - 337	0.2-0.3	66 - 240	0.1-0.2	10	1.54	1.12	Free rolling
		75	950	1 828	1.9	656	0.7	253	0.27	10	3.61	1.37	Shear mode

* Normalized Contact Pressure (NCP): NCP is the minimum and maximum measured contact stress divided by the associated inflation pressure (See also Tielking, 1989).
* * Some of the tyres tested were smooth (buffed down or trimmed) to a relatively smooth surface. This was to minimize scatter in the results owing to the tread pattern.
*** The shear mode was achieved by “shearing” the test tyre over the surface of the VRSPTA during measurement under the HVS, at an angle between 7.5 degrees to 8 degrees.

TABLE 5. PREDICTION EQUATIONS FOR THE CONTACT STRESS, INFLATION PRESSURE AND TYRE LOAD OF FREE-ROLLING TYRES

TYRE TYPE	REF No.	RANGES:REGRESSION		DATA SAMPLES (N)	CONTACT STRESS AND DIRECTION	REGRESSION CONSTANTS AND STATISTICS*				
		LOAD (kN)	INFLATION (kPa)			K_1 (kPa)	K_2	K_3	r^2 (%)	Std Error (kPa)
11.00 X 20, 14 ply, bias/cross-ply rating	I	20-50 (Single)	420-720	15	VERTICAL, Z	291.8580	0.0598	19.2474	89	80
					TRANSVERSE, Y	212.6970	-0.0809	5.6085	89	25
					LONGITUDINAL, X	-81.8359	0.1468	4.0967	36	71
11.00 x 20, 14 ply, bias/cross-ply rating	II	20-80 (Dual)	420-720	58	VERTICAL, Z	573.5620	0.7143	9.5042	69	88
					TRANSVERSE, Y	183.3980	-0.1398	5.9425	81	33
					LONGITUDINAL, X	15.8407	0.03717	4.4041	71	32
46 x 16, 30 ply rating (Aircraft)	III	20-50 (Single)	1448 (Constant for all load levels)	6	VERTICAL, Z	2016.54	0	4.7533	58	49
					TRANSVERSE, Y	138.162	0	6.4192	64	58
					LONGITUDINAL, X	55.0108	0	4.5414	97	9
315/80 R 22.5	IV	25-100 (Single)	500-1 000	89	VERTICAL, Z	80.4490	0.9021	16.1207	92	138
					TRANSVERSE, Y	106.2760	0.0129	3.2960	84	38
					LONGITUDINAL, X	210.5240	-0.2003	3.0316	83	39
425/65 R 22.5 (Wide Base)	V	25-100 (Single)	500-1 100	68	VERTICAL, Z	640.3430	0.5815	9.0165	84	130
					TRANSVERSE, Y	173.1140	0.0209	1.4367	41	49
					LONGITUDINAL, X	144.0290	-0.1312	2.1998	84	27
425/65 R 22.5 R160AZ (Wide Base)	VI	25-100 (Single)	500-1 100	56	VERTICAL, Z	605.3580	0.4530	10.1837	92	92
					TRANSVERSE, Y	30.7515	0.1696	0.9099	53	43
					LONGITUDINAL, X	122.4510	-0.10268	1.7169	88	88
425/65 R 22.5 R164BZ (Wide Base)	VII	25-100 (Single)	500-1 100	56	VERTICAL, Z	547.2840	0.8237	4.4267	89	77
					TRANSVERSE, Y	30.7515	0.1696	0.9099	53	43
					LONGITUDINAL, X	114.1210	-0.1177	2.7560	79	40

CONTACT STRESS = K_1 + { K_2 x [INFLATION PRESSURE , P]} + { K_3 x [LOAD, L]}

varied from 15 per cent to 34 per cent, when the load was increased from 50 to 100 per cent overloading. It is therefore obvious that these higher contact stress conditions should also be incorporated into the relative damage analysis in accelerated testing, especially in the case of relatively thin surfacings. It is, however, doubtful (although not impossible) that these extreme load/stress conditions will generally be found on normal roads.

GENERAL: MEASURED STRESSES AND PREDICTION EQUATIONS FOR SEVEN TYPES OF TYRES

In the next section, a rather detailed analysis is given on the seven types of tyres tested. To aid in the interpretation of data given later in Tables 4 and 5,
Figures 20 to 25 are included. These figures illustrate six different conditions during VRSPTA testing of five of the test tyres given in Table 1. In Figure 20 the three dimensional contact stress results of the HVS tyre (Type I) are illustrated. Note the effect of tyre tread in the rather irregular pattern of all three stresses. Typical results of the aircraft tyre and the wide-base tyres are given in Figures 21 to 25. For both the aircraft tyre (Type III) and the 315/80 R22.5 tyre (Type IV), the maximum vertical contact stress occurred at the tyre centre at the load and inflation pressure given. The wide-base tyre in Figure 23 (Tyre Type V) experienced some maximum vertical and transverse stresses at the tyre edges at the rated load and inflation pressure. Figures 24 shows the results of another wide-base tyre at rated load and inflation pressure with the maximum stress at the tyre centre. In Figure 25 an overloaded case on the same tyre as in Figure 24 with the maximum stresses at the tyre edges is given.

In Figure 25d a typical imprint, i.e. contact patch with vertical contact stress values from the VRSPTA is illustrated. This imprint is directly obtained by the measured data and could therefore be used in subsequent analysis such as 3-D finite element, etc.

Maximum contact stresses and stress ratios. In this section a short summary of the measured maximum stresses obtained for the various tyres (seven types) tested is given. The most important of the measured data are summarized in Table 4. This table also gives the ranges of maximum stresses in the X, Y, Z directions found for the various tyres, together with the maximum stress ratios. As discussed for the smooth tyre, the relative magnitudes of the three stress components measured with the VRSPTA (i.e. Vertical (Z), Transverse (Y) and Longitudinal (X)) are expressed as the ratio between the maximum of these stresses. For all the cases investigated these ratios are given in the last three numerical columns in Table 4. In terms of tyre inflation pressure, the maximum stresses are also normalized, using the normalized contact pressure (NCP), and are also given in the table.

Discussion of the results in Table 4. The table indicates that the highest transverse stresses are obtained under the bias/cross-ply tyres under a "slow-moving free-rolling" condition. These stresses are between 21 per cent and 36 per cent of the maximum vertical stress. Most of the radial types of tyres tested here give transverse stresses between 11 per cent and 18 per cent of the maximum vertical stresses. In general, for the tyres tested here under "slow-moving free-rolling" conditions it was found that the *radial tyres* give an average ratio of **10 : 1.6 : 1.3**. For the *bias/cross-ply tyres* the average ratio is **10 : 3 : 1.5**. The smooth bias/cross-ply tyres seem to result in higher transverse ratios (up to 3.6). In terms of the NCP, it is seen that these ratios seldom exceed two (2), and, where they exceed this, it is associated with extremely high loading. This finding agrees well with an earlier theoretical finding by Tielking (1989).

Sideways shear (i.e. cornering). In order to obtain an idea of the *additional* transverse shear forces (stresses) that may develop under a condition of cornering, the HVS test tyre was "sheared" over the surface of the VRSPTA by moving the tyre during testing towards the one side of the VRSPTA at an angle of approximately 7.5 to 8 degrees. The test results indicate that the transverse stress increases by approximately 30 kPa/degree for the tyre Type IV, and approximately 50 kPa/degree for the wide-base tyres. In terms of the ratio of maximum stresses, the transverse ratio increases to a range between 2.6 and 3.61. (See Table 4.)

Estimation of the three-dimensional tyre/pavement contact stresses. Several prediction equations were developed for the estimation of the three-dimensional maximum contact stresses of 7 different types of tyres. Basically, a simple multiple linear regression analysis was used relating the measured maximum contact stress with both the inflation pressure and tyre load. These equations are summarized in Table 5, for the Vertical (Z), Transverse (Y) and Longitudinal (X) stresses. The analysis indicated that both the tyre inflation pressure and load influence the contact stresses for all three directions. Some regression statistics are also included in the table. The correlation coefficient r^2 is generally high for all the vertical stresses, except for one or two cases. The standard error in predicted contact stress associated with these correlations varies between 9 kPa and 138 kPa. The general form of the prediction equation is given below:

CONTACT STRESS = K_1 + { K_2 x [INFLATION PRESSURE , P]} + { K_3 x [LOAD, L]}..................Eq 4

where:

Contact Stress in kPa;
Inflation pressure, P in kPa;
Tyre load, L in kN, and
K_1, K_2 and K_3 - the regression coefficients from Table 5.

The purpose of these prediction equations is to assist engineers and practitioners to improve on the estimation of tyre/pavement contact stresses for use in pavement design, rehabilitation design, pavement evaluation, improved mechanistic design, possible tyre evaluation as well as the vehicle/road dynamics problem (Winkler, 1995). In Figures 26 and 27 the prediction equations are given in graphic format over the range of loading and inflation pressures used for the regression. It is important *not* to apply these equations (or graphs) outside the indicated ranges, as this may lead to some serious errors in the estimated contact stresses.

Vertical contact stress prediction at rated tyre load and inflation pressure. For the practical purpose of estimating the actual maximum vertical contact stress the regression equations given in Table 5 can also be used very effectively. Analysis of five of the tyres tested indicated that the predicted maximum vertical stress from the regression equations with the rated tyre load and rated inflation pressure is between 5 to 10 per cent of that measured with the VRSPTA. Analysis of the maximum stresses at rated load and tyre inflation pressure of the five cases investigated here resulted in normalized contact pressure ratios (NCP, see Table 4) between 1.6 and 2.7. This result compares favourably with similar findings from Yap (1988), where the NCP ranged between 1.2 and 2.0. It is therefore clear that the vertical stress in pavement design and analysis is grossly under-estimated by previous methods by a factor of 1.6 to 2.7 times the inflation pressure in South Africa.

It is therefore suggested that the improved methods for estimating the contact stress given here be used in pavement design and analysis until further research proves otherwise.

ANALYTICAL INVESTIGATION INTO SOME EFFECTS OF TWO-DIMENSIONAL AND NON-UNIFORM TYRE CONTACT STRESSES ON THIN ASPHALT SURFACINGS

Introduction. In order to study some effects of the two-dimensional and sometimes highly non-uniform tyre/pavement contact stress distributions on relatively thin asphaltic surfacings, a relatively simplistic axi-symmetric two-dimensional finite element method was used. For the purposes of this study it was decided to limit the analysis to a single wheel load application on a typical B-category type of pavement structure (TRH4, 1996). This pavement is normally designed to have a relatively thin (40 mm) asphaltic surfacing layer, and is commonly used in many areas in South Africa.

This pavement was also selected for analysis here since a great deal of HVS testing had been done on the pavement, including several rehabilitation options (Steyn et al, 1996). The 40 mm asphaltic surfacing was constructed as one of the candidate rehabilitation options on a “cracked-and-seated” lightly cemented base/subbase layer, tested with the Heavy Vehicle Simulator (HVS) (Steyn et al, 1996).

Test pavement and materials. The pavement structure is illustrated in Figure 28, together with the linear elastic parameters used for the modelling with the finite element method. Since the asphalt is relatively thin, and the analysis aimed at the behaviour under relatively high speed conditions, it was decided to limit the study to instantaneous loading conditions. Therefore the time dependent (viscous) behaviour of the asphalt layer was considered to be limited and not included here. The authors believe that for this condition the linear elastic solution (i.e. instantaneous loading) will suffice for the purposes discussed here.

In the following section several load/stress idealizations are compared to one another, based on analysis of the pavement structure given in Figure 28.

Finite Element Analysis (FEA). The axi-symmetric finite element model developed for this investigation included both linear and/or non-linear material models as specified, and is based on the formulations given by Owen and Hinton (1980). The load/stress is idealized by a maximum of two components, namely vertical pressure on specified element faces on the surface (i.e. top row elements), as well as the possibility of introducing outward or inward (or both) shear forces at the top row of elements. For the investigation discussed here a mesh consisting of a total of 190 elements, with maximum radial distance 1 300 mm from the circular load to a depth of 1 300 mm was used. The model and mesh used in this analysis are illustrated Figure 29.

Analytical parameters studied. Since there is a wide range of pavement behaviour models worldwide, most of which are empirically based, it was decided to limit this investigation to some of the *basic* analytical descriptions of the stress/strain or energy *on top or inside* the individual layers in the pavement system under investigation. This approach is similar to the one used by Perdomo et al (1993). The purpose here was also not to develop new failure laws (i.e. transfer functions) for asphaltic surfacings at this stage, but rather to illustrate potential damage zones, especially in or at the asphalt surfacing layer, by using well-known analytical methods. These analytical methods may, however, be used as a *basis* for determining the limiting stress/strain/energy at which failure may occur in these materials, but this is outside the scope of this paper.

Although the finite element model can also treat the material as non-linear, this investigation is limited to the linear elastic case as discussed above (i.e instantaneous loading), but with non-uniform vertical and transverse load/stress idealization (where applicable). The purpose is therefore to obtain some indications of the location and relative magnitude of critical zones inside pavements with thin surfacings, *relative to the standard uniformly loaded* case. In South Africa the standard load configuration is an 80 kN dual wheel load with a uniformly distributed pressure of 520 kPa. In practice, this configuration is applied using the well-known linear elastic multi-layer pavement idealization, with full friction between all layers. The analytical parameters used here are the following:

- **Bulk stress**, (Volumetric behaviour);
- **Octahedral shear stress** (Distortion behaviour);
- **Strain Energy of Distortion (SED)**. The SED

$$J'_2 = \frac{1}{2}[(\sigma_{rr} - \sigma_{bulk})^2 + (\sigma_{tt} - \sigma_{bulk})^2 + (\sigma_{zz} - \sigma_{bulk})^2] +$$

  is another parameter to describe distortional characteristics of, in this case, linear elastic materials. It is basically the amount of work per unit volume, or strain energy per unit volume (Timoshenko, et al, 1951).

The bulk stress is defined as:

$$\sigma_{bulk} = \frac{\sigma_{rr} + \sigma_{tt} + \sigma_{zz}}{3} \quad \ldots\ldots\ldots\ldots\ \textbf{Eq 5}$$

with:

σ_{rr} = *radial stress*

σ_{tt} = *tangential stress*

σ_{zz} = *vertical stress*

The Octahedral stress is defined as:

$$\tau_{oct} = \sqrt{\frac{2}{3} J'_2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ \textbf{Eq 6}$$

where:

$$\sigma_{rz}^2 + \sigma_{rt}^2 + \sigma_{tz}^2 \ldots\ldots\ldots\ldots\ldots\ldots \textbf{Eq 6a}$$

The Strain Energy of distortion (SED) is given by:

$$SE/Volume = \frac{1}{2}[(\sigma_{rr}\epsilon_{rr} + \sigma_{tt}\epsilon_{tt} + \sigma_{zz}\epsilon_{zz}) +$$

$$(\tau_{rt}\gamma_{rt} + \tau_{tz}\gamma_{tz} + \tau_{rz}\gamma_{rz})] \quad \ldots\ldots\ldots\ \text{Eq 7}$$

where σ_i, τ_{ij} are the elastic stress components and $_i$, γ_{ij} are the elastic strain components. The strain energy can be divided into two parts: one caused by distortion and the other by volume change. The distortional part is referred to as Strain Energy of Distortion (SED), and is defined below as:

SED/Volume:

$$SED/Volume = SE/Volume - [\frac{(1-2\ \ )}{6E}(\sigma_{rr} + \sigma_{tt} + \sigma_{zz})^2]$$

where is the Poisson's ratio and E is the elastic modulus.

Types of load/contact stress idealizations for analysis purposes. Several types of load/contact stress idealization were evaluated in this study. These cases are summarized in Table 6 and in Figure 30. All the cases refer to the basic pavement structure given in Figure 28 and to the analysis model in Figure 29.

Table 6. Types of load/contact stress idealization studied

TYPE	TYPE OF CONTACT STRESS IDEALIZATION	
	VERTICAL	TRANSVERSE (Lateral)
I	Uniform, 520 kPa at 20 kN loading	None
II	Triangle, max at tyre centre, 520 kPa	None
III	Triangle, max at tyre edges, 520 kPa	None
IV	Uniform, 520 kPa	Triangle, Max 260 kPa, inward
V	Uniform, 520 kPa	Triangle, Max 260 kPa, outward
VIA	Tread, max centre rib - VRSPTA measured at 520 kPa ,20 kN.	Inward and outward lateral, as measured
VIB	Tread, max at tyre edges - VRSPTA measured at 720 kPa, 20 kN.	Inward and outward lateral, as measured
VII	Tread, max edge rib - VRSPTA measured at 420, 40 kN	Inward and outward lateral, as measured

The seven types of load/contact stress idealizations are also illustrated in Figure 30, showing the variations compared to the standard case (Type I).

Results and discussion. The results of the analytical study of the basic cases of types of instantaneous stress distributions given in Table 6 are summarized in Table 7. For the pavement structure investigated here it was found that both the non-uniformity of the stress idealization used and the applied shear stresses influenced both the *position* and *magnitude* of the bulk stress, octahedral stress and the SED in the pavement layers relative to the normal uniformly distributed stress, Type I. Table 7 indicates that the maxima of these analytical parameters are mostly confined to *within* or at the *bottom* (37.75 mm) of the asphaltic surfacing layer. It is also interesting to note that with tyre edge conditions (i.e Types III, IV and VII), the maxima of the analytical parameters are located away from the tyre centre closer to the position of maximum stress application (i.e tyre edge). In the cases investigated here the maxima remain at the bottom of the thin asphalt surfacing. It is believed that this is controlled by the instantaneous loading, and that at slower speeds (i.e creep loading) the asphalt will behave in a more viscous manner in which case the maxima may re-orientate to other positions *within* the asphalt layer. Nevertheless, with tyre edge loading conditions (i.e underinflation/overloading), two maxima, one at each tyre edge will result in the asphalt surfacing layer. As an illustration of the analysis method used here, some results of a comparison of the SED contour plots under Type I (the standard) load/stress idealizations and the relatively overloaded/under-inflated case (Type VII) are given in Figures 31 and 32. From these illustrations and the results in Table 7 it is clear that not only is the magnitude of the SED's different, but also occurs at different locations under the tyre. For load/stress Type I, the maximum SED is 505 MPa/m^3 directly under the centre of the tyre at the bottom of the thin asphalt surfacing (38 mm), while the SED of load/stress Type VII is 606 MPa/m^3, and occurs approximately 59 mm from the tyre centre, also at the bottom of the asphaltic surfacing. Note also the irregular contour lines in Figure 32 compared to those in Figure 31. This is due to the tyre tread. This is considered significant, at least for thin surfacing layers, since the maxima of the parameters therefore occur at ***both sides*** of the tyre centre. It also indicates potential *additional damage* relative to the accepted standard uniform loading case, Type I, where the maxima occur only at the tyre centre. This may not be the best illustration of this behaviour, but certainly points to the fact that overloaded/under-inflated tyres may cause potentially more damage to a this type of pavement than a tyre at its rated load and inflation pressure. The expected damage may include structural distress such as cracking, rutting, crushing or a combination thereof, in or at the interface of the layer directly beneath the thin asphaltic surfacing layer.

It is also interesting to note that in some cases the traditional use of a circular uniform stress distribution (Type I) results in higher SED's than the actual non-uniform distribution, with lateral loading (Type VIA, Table 6). The implication of this finding should be investigated further, but may suggest possible "over-designing", using higher stress conditions than really exist. It is, however, advisable to do a sensitivity analysis, using several stress distributions incorporating the most realistic pavement loading/stress situation that is to be catered for during the design and/or evaluation of the pavement.

A comparison of the bulk stress between Types I and VIA shows that for Type VIA it is approximately 26 per cent higher than that for Type I. In both cases it occurs at the tyre centre. This could have both positive and negative implications, depending on the stress stiffening/softening and viscous behaviour of the surfacing material. For stress stiffening materials (like confined granular material) the higher bulk stresses could result in an increased effective elastic moduli under the tyre. For stress softening and more viscous materials (like hot asphaltic surfacings, or wet clay for that matter), these higher bulk stresses could result in some horizontal flow of the materials, squeezing out or inwards from the tyre contact patch, depending on inward or outward shear. Obviously the flow will occur after some initial densification in the asphalt layer, depending on the after-construction void content.

Practical example from HVS testing. Following the method described above, a detailed analysis was done on the accelerated pavement test results of two HVS test sections (HVS04 test no. 346A4 and 347A4), with a thin semi-gap graded asphalt surfacing. See Figure 29. In this case, using the contact stress Type VIA[2] on HVS section 346A4, transverse and longitudinal fatigue cracking resulted on the surface of the HVS test section after approximately 1.4 million standard (40 kN, 520 kPa) load/stress cycles. On the other HVS section (347A4) on the same pavement, a 70 kN dual wheel load at 520 kPa inflation pressure was used to study the relative damage in terms of fatigue cracking, resulting from overloading (by load) on this type of pavement. The stress idealization used here was similar to Type VII in Table 6. This section cracked in a similar way to that of the previous section at 40 kN dual wheel load, but only after approximately 2 million load/stress cycles. Clearly this illustrates some anomaly since it was expected that the higher load would result in earlier cracking than the lower load on a similar pavement structure. As a first step in the analysis effective elastic moduli were back calculated using simple linear elastic multi-layer theory based on measured depth deflections from the Multi-Depth Deflectometer (MDD) (De Beer et al, 1988, Steyn et al, 1996). This analysis resulted in the

[2] Suggested it be the HVS standard 40 kN dual load @ 520 kPa inflation pressure, if the method described here is used for analysis of HVS results.

effective elastic moduli of the base and lower layers of the latter HVS test section being generally higher than those for the first section (346A4). This indicates that the pre-cracked cemented base and lower layers were slightly stress stiffening, resulting in relatively higher effective elastic moduli for the 70 kN section. These moduli values are indicated in Figure 29. The linear elastic theory with Type I loading could only partially explain why the 40 kN section (346A4) cracked earlier than the 70 kN section (347A4). Use of the analytical parameters of bulk stress/strain, octahedral stress/strain, and hence the SED on both these sections, indicated that the 70 kN section gave *relatively lower values* for all the parameters studied. See Table 8. For instance, the strain energy of distortion (SED) is approximately 40 per cent lower on the 70 kN section than on the 40 kN section. In addition, by comparing the SED from Type I loading (the results of Type I load/stress idealization are given in bold and italics in Table 8), it can be seen that not only are the SED and Octahedral stress/strain lower for Type I, but that they occur at the tyre centre, at the bottom of the asphalt layer. Furthermore for Type I loading, some tensile stresses and strains are calculated on the surface of the asphalt surfacing, outside the tyre contact patch (approximately 204 mm from the tyre centre). This is markedly different for the results from the Type VII load/stress idealization, where some tensile stresses were calculated at the bottom of the asphalt layer, away from the tyre centre but inside the tyre contact area. On the other hand, Type VII loading for the 70 kN section indicates maxima not only at different positions from Type I and the 40 kN section, but also relatively lower values. Based on the foregoing, the authors believe that these lower values of the analytical parameters partly explain the anomaly found with these HVS test sections, where the fatigue cracking of the thin surfacing occurred more rapidly on the 40 kN section than on the 70 kN section. Further analysis based on a visco-elastic asphalt model and varying the effective elastic moduli of the different supporting layers should however be done for more conclusive results on this matter. This, however, is outside the scope of this paper.

It is also interesting to note that the rutting on the surfacing, at cracking in the asphalt layers, compared favourably with each other: 3.5 mm on the 40 kN section (Section 346A4) and 5.5 mm on the 70 kN section (Section 347A4). A study of the instantaneous bulk stress (in compression) on the 70 kN section shows it is only 5 per cent higher than that for the 40 kN section (See Table 8). Note also that the Type I solution resulted in quite different bulk stresses for the two sections.

Based on the findings above, and those indicated by others (Perdomo et al, 1993), the authors are confident that the approach described here will have practical value. The calculations indicate an improved explanation of the macro observed behaviour found on accelerated pavement test sections, as was illustrated by the case investigated here under HVS testing.

Table 7. Summary of the analytical parameters calculated for the different types of contact stress idealizations given in Table 6 and Figure 30

TYPE	DISPL. (micron)	STRAIN ENERGY OF DISTORTION (SED) (MPa/m^3)					
		RR	ZZ	MINIMUM	RR	ZZ	MAXIMUM
I	464.23	1254.92	650	0.00	1.13	37.75	505.21
II	187.492	1254.92	650	-0.01	1.13	37.75	217.97
III	277.232	1254.92	766.19	-0.01	71.13	37.75	132.61
IV	449.388	1254.92	766.19	0.00	38.87	37.75	427.55
V	479.072	1254.92	766.19	0.00	1.13	1.13	1337.29
VIA	325.198	1254.92	1050	0.00	1.13	37.75	388.98
VIB	329.225	1254.92	1050	0.00	1.13	37.75	599.61
VII	500.733	1254.92	43.38	0.00	58.87	37.75	606.05
		BULK STRESS (kPa)					
		RR	**ZZ**	**MINIMUM**	**RR**	**ZZ**	**MAXIMUM**
I		1.13	1.13	-1295.79	1.13	37.75	472.06
II		1.13	1.13	-942.72	1.13	37.75	385.40
III		91.13	1.13	-738.50	81.13	37.75	252.22
IV		58.87	1.13	-1116.35	41.13	37.75	449.12
V		1.13	1.13	-2093.39	1.13	37.75	538.05
VIA		1.13	1.13	-1644.34	1.13	37.75	501.34
VIB		1.13	1.13	-2263.75	1.13	37.75	670.38
VII		85	1.13	-2019.58	65	37.75	584.54
		OCTAHEDRAL STRESS (kPa)					
		RR	**ZZ**	**MINIMUM**	**RR**	**ZZ**	**MAXIMUM**
I		1254.92	55	0.01	1.13	37.75	631.19
II		1254.92	55	0.00	1.13	37.75	414.59
III		1254.92	55	0.01	71.13	37.75	323.65
IV		1254.92	55	0.02	38.87	37.75	580.87
V		1254.92	55	0.01	1.13	1.13	1027.09
VIA		1254.92	43.38	0.01	1.13	37.75	553.85
VIB		1254.92	43.38	0.01	1.13	37.75	687.65
VII		1254.92	43.38	0.01	58.87	37.75	691.60

RR = RADIAL DISTANCE FROM THE LOAD IN mm
ZZ = PAVEMENT DEPTH IN mm

Table 8. Comparison of the analytical parameters* of the two HVS04 test sections investigated here with both the instantaneous non-uniform pressure and the instantaneous uniform pressure solution.

ANALY-TICAL PARA-METER	MIN/ MAX	HVS SECTION 346A4 (40 kN, 520 kPa)			HVS SECTION 347A4 (70 kN, 520 kPa)		
		VALUE	RADIAL DISTANCE (mm)	DEPTH (mm)	VALUE	RADIAL DISTANCE (mm)	DEPTH (mm)
BULK STRESS (kPa)	MIN	-1 644	1.13	1.13	-1 731	85	1.13
		-1 296*	***1.13***	***1.13***	***-882***	***1.13***	***1.13***
	MAX	501	1.13	38	151	79	38
		472	***1.13***	***38***	***35***	***204***	***1.13***
BULK STRAIN (micro strain)	MIN	-216	11	43	-209	85	1.13
		-316	***1.13***	***43***	***-158***	***1.13***	***44***
	MAX	61	1.13	38	18	79	38
		57	***1.13***	***38***	***4***	***204***	***1.13***
OCT. STRESS (kPa)	MIN	0	1 255	43	0	1 100	67
		0	***1 255***	***55***	***36***	***1 255***	***67***
	MAX	554	1.13	38	535	91	1.13
		631	***1.13***	***38***	***337***	***1.13***	***38***
OCT. STRAIN (micro strain)	MIN	0	1 255	44	0	1 100	190
		0	***1 255***	***55***	***0***	***1 100***	***76***
	MAX	930	1.13	44	706	81	44
		1 209	***1.13***	***67***	***596***	***1.13***	***67***
SED in MPa/m^3	MIN	0	1 255	44	0	1 100	15
		0	***1 255***	***650***	***0***	***1 100***	***1 050***
	MAX	389	1.13	38	234	71	38
		505	***1.13***	***38***	***144***	***1.13***	***38***
DEFLEC-TION (micron)	MAX	315	0	0	262	0	0
		449	***0***	***0***	***248***	***0***	***0***

* A minus indicates a state of ***compression***.

** ***Bold Italic indicates the traditional 520 kPa uniform pressure solution (Type I, Table 6 and Figure 27).***

It is also believed that this type of approach will be valuable in the everyday analysis of pavements, especially of pavement surfacings in need of rehabilitation of some kind, as well as in the study of the effect of increased tyre inflation pressures and loads on existing road systems.

SUMMARY AND CONCLUSIONS

This paper describes a system developed for the simultaneous measurement of tyre/pavement interface contact stresses of slow-moving pneumatic truck tyres. The Vehicle-Road Surface Pressure Transducer Array (VRSPTA) has been developed over the last few years in South Africa for the improved quantification of the vertical, transverse and longitudinal tyre/pavement interface contact stresses. This instrument was needed since many years of accelerated pavement testing (APT)) has been done on pavements with relatively thin surfacing layers, using the Heavy Vehicle Simulator (HVS) assuming a uniform vertical stress distribution in all analysis done. In addition to the APT research, field evidence also suggested that an improved understanding of the actual contact stresses is urgently needed, since the evidence pointed to several failures from the "surface", rather than from a lack of bearing capacity of the pavements. This therefore necessitated improved definitions of the associated contact stresses mentioned above.

The VRSPTA (SIM MK II) was used in this study to investigate the three-dimensional tyre/pavement contact stresses of seven different types of tyres, ranging from bias/cross ply, to radials, including three types of wide-base tyres. These tyres were loaded over wide ranges of load and inflation pressure. Several basic concepts of measured tyre/pavement contact stresses are highlighted. The stress ratios between the maximum of the three stresses were used to define some differences between the different tyre types. It was clearly demonstrated that most of the time the maximum vertical contact stresses are indeed *higher* than the tyre inflation pressure. Even under the rated load and inflation pressure these contact stresses can be up to twice the tyre inflation pressure. In addition, several predictive equations for 3-D contact stresses were developed for the tyres tested to allow a relatively accurate estimation of the maximum expected tyre/pavement contact stresses for a fixed load and inflation pressure condition.

A detailed pavement analysis was also done, using a finite element approach in order to define the non-uniform contact stresses, both vertical and transverse. The analysis was confined to the instantaneous loading on a pavement consisting of a relatively thin (< 50 mm) asphaltic surfacing layer since this is typical of many pavements in South Africa. The analysis indicated that the strain energy of distortion, bulk stresses and octahedral shear stress (i.e. analytical parameters) in the pavement under instantaneous loading change as a function of the applied stress. It was demonstrated that the maximum of these analytical parameters occurs close to the maximum of the applied stress. This effectively means that a tyre loaded at the rated load and inflation pressure may produce maximum stresses, and hence the calculated analytical parameters at the tyre centre position near the bottom of the thin surfacing. On the other hand, an overloaded/under inflated tyre may result in two maxima located within the asphalt layer under the maximum applied stress position (i.e. tyre edges) in this case. It is also interesting to note that the conventional method using a uniform vertical stress distribution, causes some tensile stresses on the surface of the asphaltic layer, outside the tyre contact patch which may suggest that load/stress associated cracking originates from the surface of the asphalt layer downwards. By using the method of strain energy of distortion (SED) based on instantaneous non-uniform and shear (lateral) stress application, the relative magnitude of the octahedral stress seems to suggest possible damage from the surface of the asphalt layer. It appears therefore that improved understanding and definition of the applied contact stress idealization may result in different answers from those achieved by conventional methods. Advanced analytical tools should be made available to practitioners in order to take the identified differences in contact stress into account during analysis and design of flexible pavement structures.

It is concluded that an effective method has been developed for the measurement of tyre/pavement contact stresses, and that the information gained resulted in improved methods for the estimation of the vertical, transverse and longitudinal forces (i.e. stresses), of slow-moving pneumatic tyres. Also, the use of non-uniform and shear (lateral) stresses in the design and analysis of flexible pavements with thin surfacings indicates the possibility of large potential differences compared to conventional design and analysis methods.

RECOMMENDATIONS

It is recommended that the various methods describe here be used in practice as well as in accelerated pavement test facilities for the improved definition of the tyre/pavement contact stress problem. It is also recommended that analysis methods be improved to incorporate non-uniform vertical and lateral shear stress, and that it should be made available to practice as soon as possible.

The following are specific recommendations for further research:

- Include general and advanced tyre characteristics such as tyre stiffness, rubber moduli, temperature effects, etc, in further studies using the VRSPTA. The goal here should be to develop a simplistic tyre model to be used for pavement design purposes.

- Study the effects of vehicle/tyre speed on the distribution of the three stress components for typical trucks. Limited work in this regard has already started and it is clear that tyre/wheel dynamics may dominate the shape of especially the vertical contact stress distribution.

- Study the effects of differential wear on truck tyres, since some evidence points to large variations in contact stress distributions owing to local wear patches on the tyre tread (De Beer et al, 1996). Some research into this aspect is already given by Changizi (1994).

- Study the effect of variable friction on the surface of the VRSPTA, as well as different heights of the measuring pins.

- Develop an improved tyre model for use in both static and dynamic analysis of pavement structures.

- Investigate the feasibility of the principle of using the VRSPTA technology for the development of future "Stress-in-Motion" (SIM) systems. This could enhance the current "Weigh-in-Motion" (WIM) technology. The aim here should be to obtain the contact stresses directly under moving vehicles, as opposed to only the axle loads, as also suggested by Cunagin et al, (1986). Such a demonstration project is currently being constructed on National Highway 1 (N1) near Montsole, north of Pretoria in South Africa.

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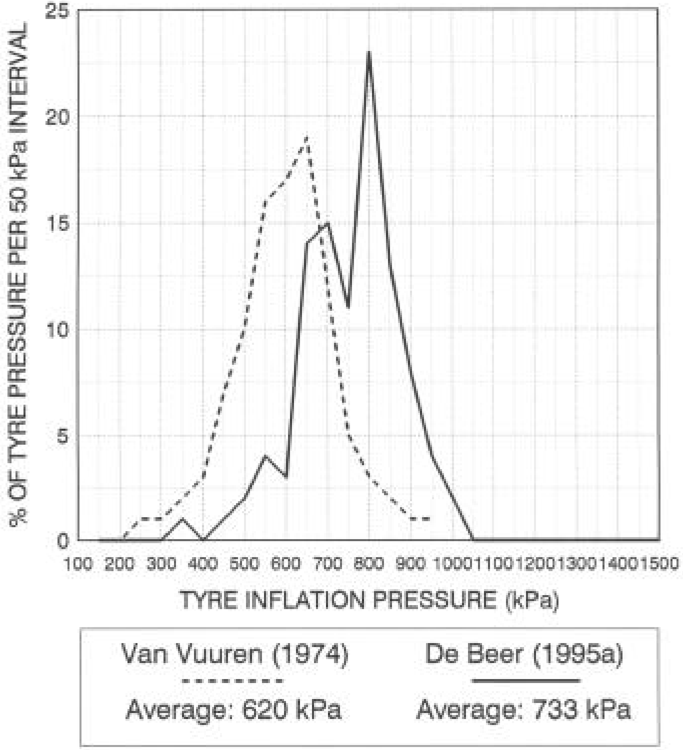


Figure 1a
Average measured tyre inflation pressure distributions of heavy vehicles (axle load > 7 000 kg) on roads in the province of Gauteng, South Africa (1974 to 1995)

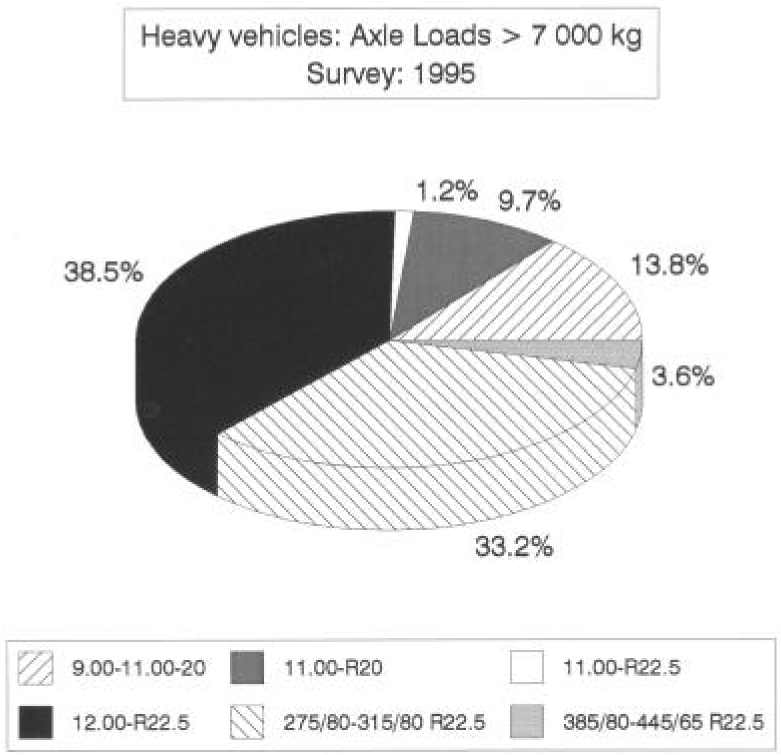


Figure 1b
Distribution of heavy truck tyre types in Gauteng and KwaZulu-Natal in South Africa

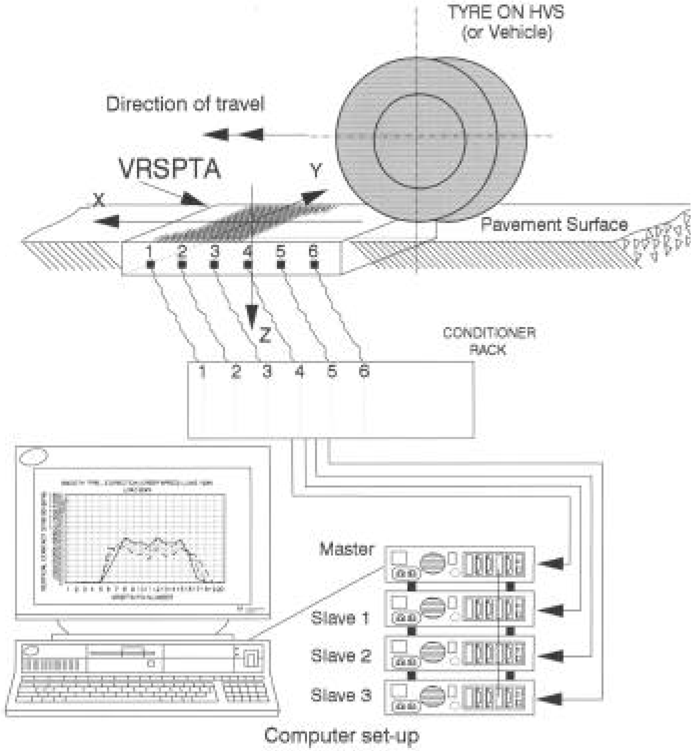


Figure 2
Layout of the VEHICLE-ROAD SURFACE PRESSURE TRANSDUCER ARRAY (VRSPTA) system
(SYSTEM: SIM MK II)

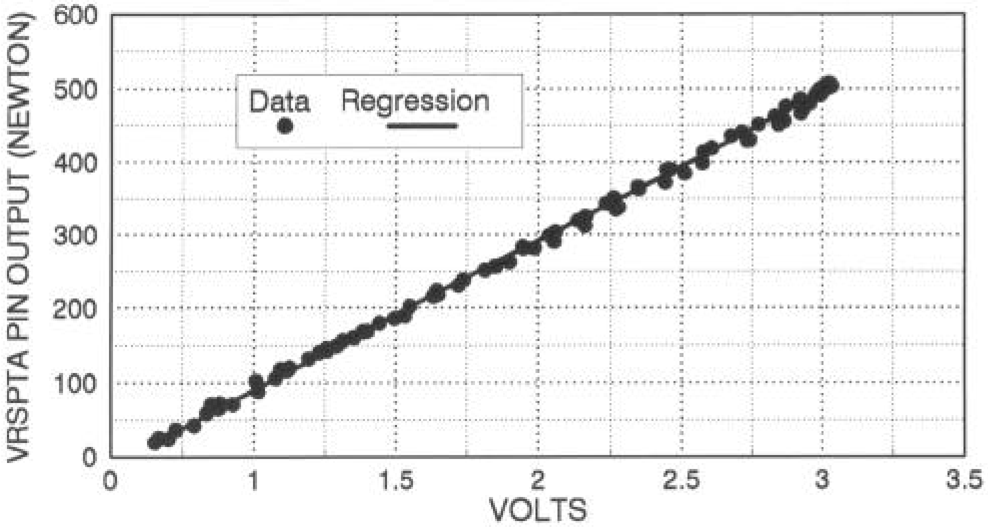


Figure 3
Typical result from calibration of the VRSPTA relating voltage output to load of the instrumented pins

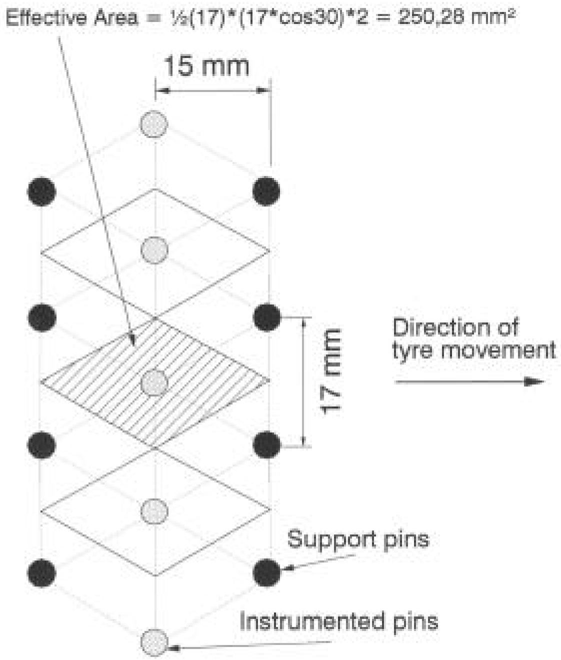


Figure 4
Effective Diamond Shaped Area used for the contact stress calculation in VRSPTA

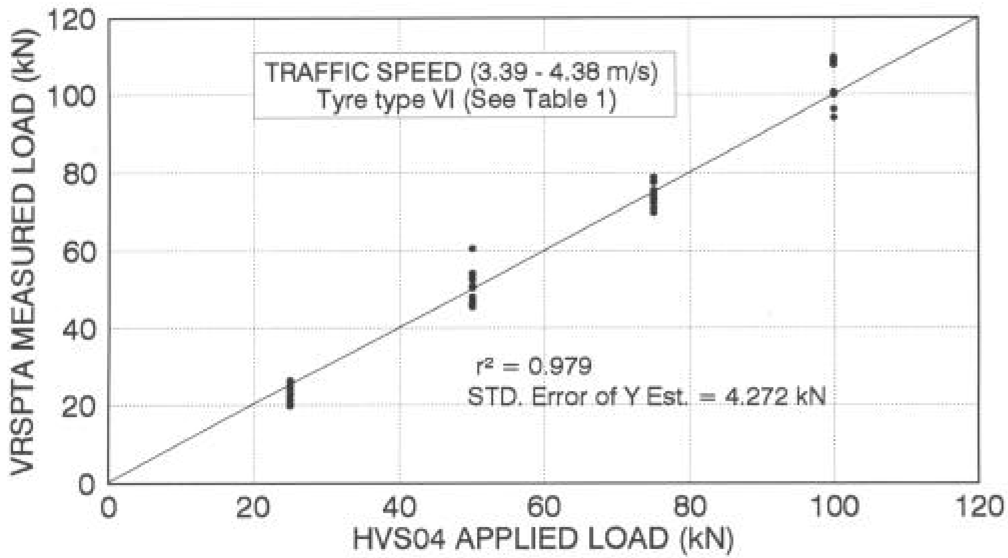


Figure 5
Accuracy of the VRSPTA relative to HVS04 applied load (random error)

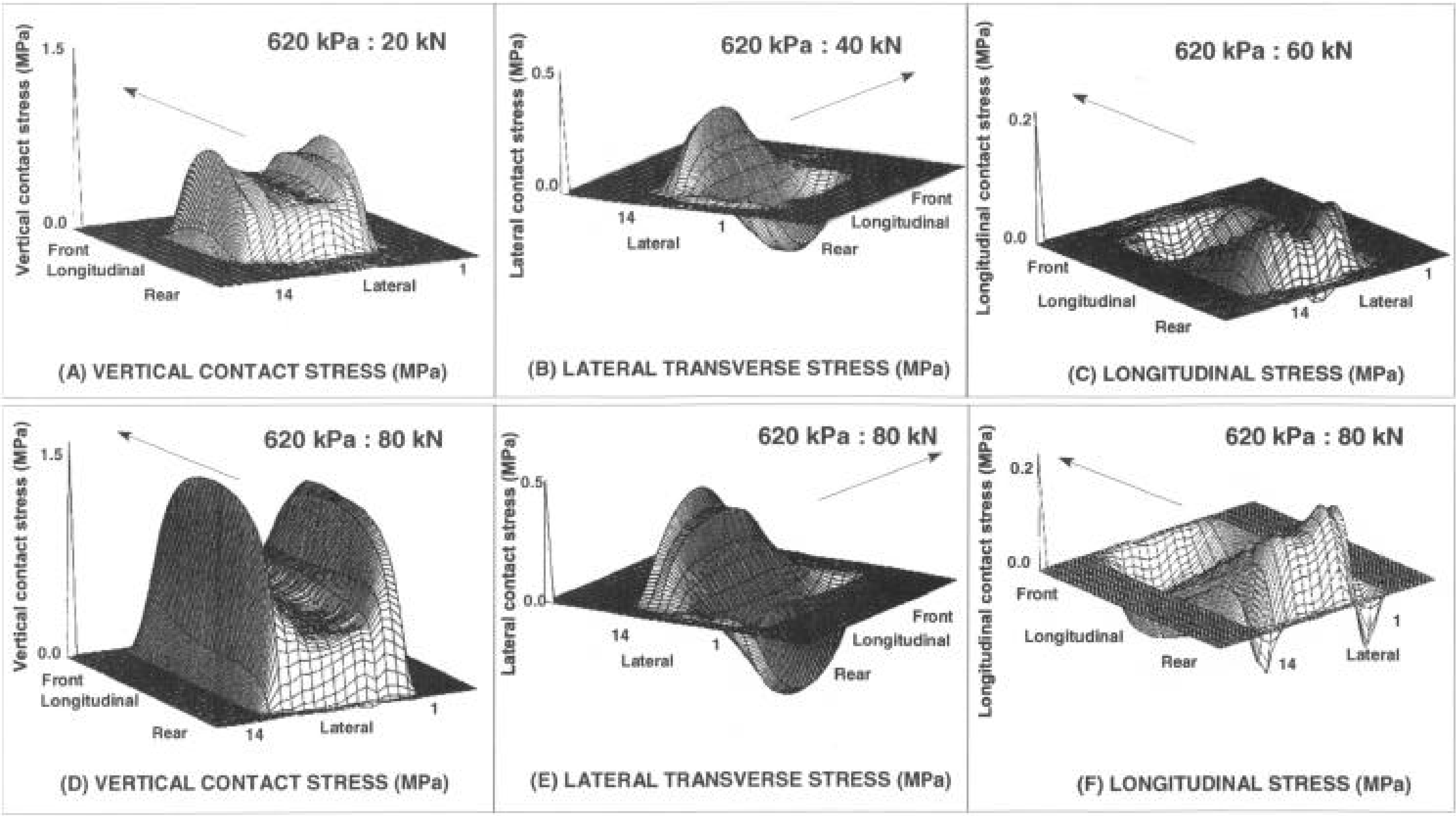


FIGURE 6 : Typical contact stress distributions measured with the VRSPTA system for a slow moving (1,2 km/h) free rolling smooth single truck tyre (Goodyear 11.00 X 20, 14 Ply rating)

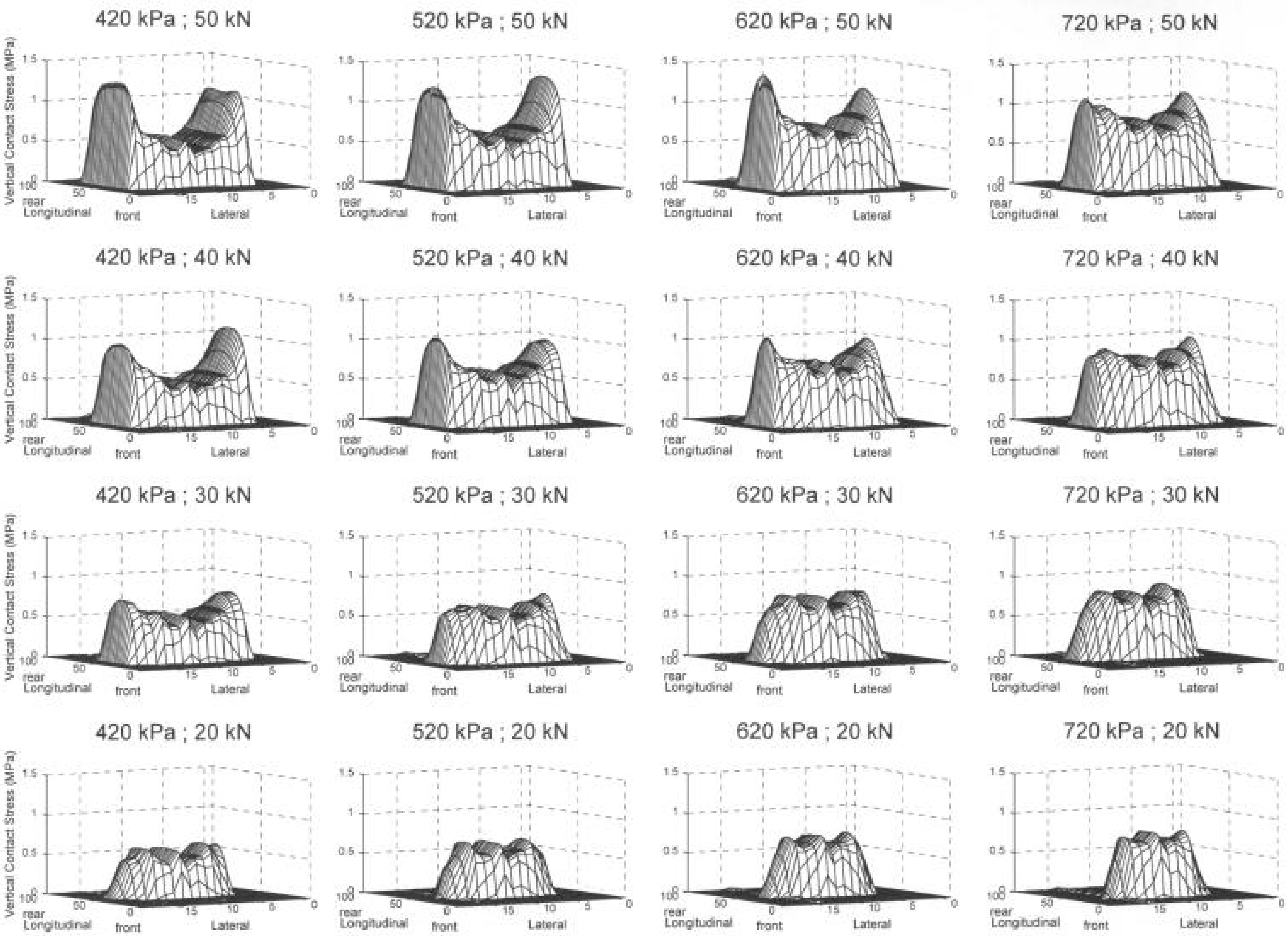


Figure 7: Graphic illustrations of the tyre load/inflation pressure relationship on the vertical contact stress distributions of a slow moving (1,2km/h) single bias/cross ply HVS tyre with tread grooves: Tyre TYPE I, Table 1 (Inflation Pressure:420kPa to 720kPa, Tyre Load: 20kN to 50kN)

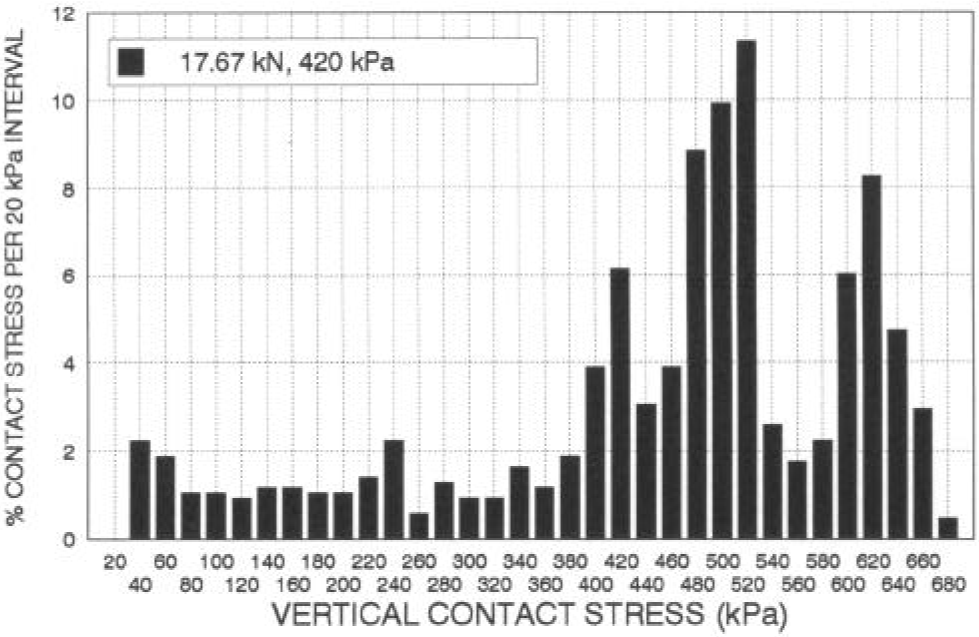


Figure 8
Vertical contact stress distribution of the smooth tyre
at 17.67 kN, 420 kPa, Test Speed 0.32 m/s

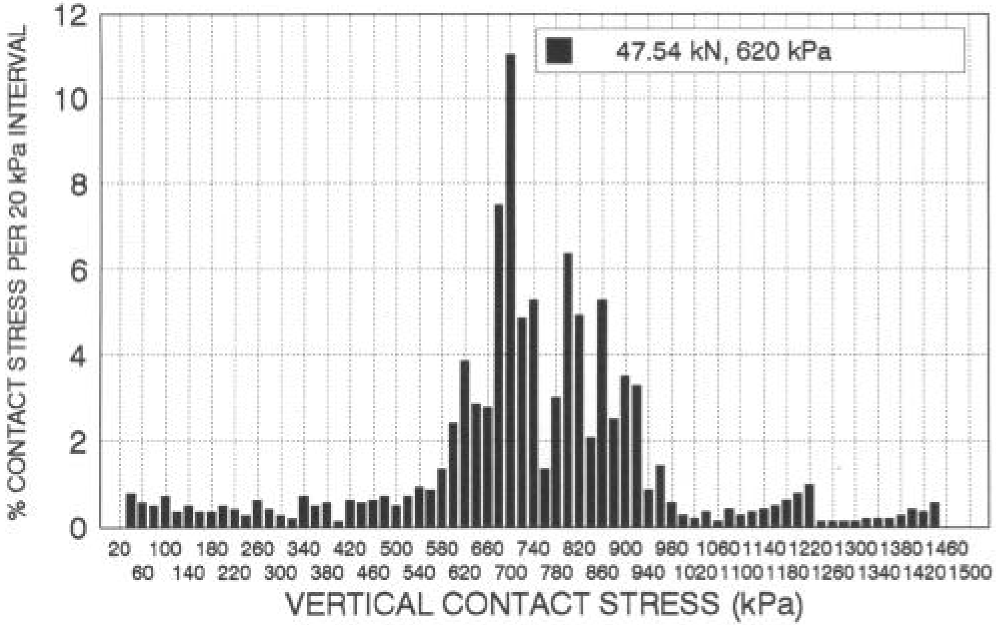


Figure 9
Vertical contact stress distribution of the smooth tyre
at 47.54 kN, 620 kPa, Test Speed 0.32 m/s

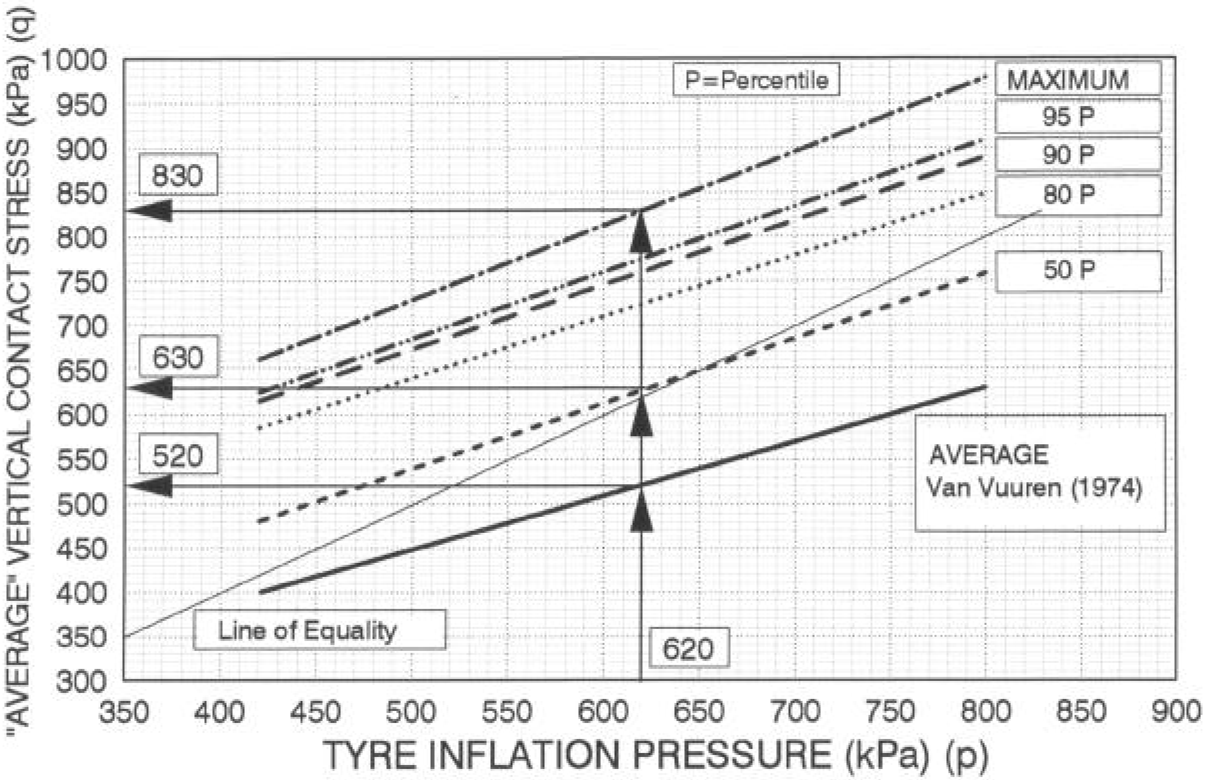


Figure 10
Relationships between "average" vertical contact stress and inflation pressure for the smooth tyre at the rated load and inflation pressure in comparison with Van Vuuren (1974) - solid line
(11.00-20, 14 ply tyres)

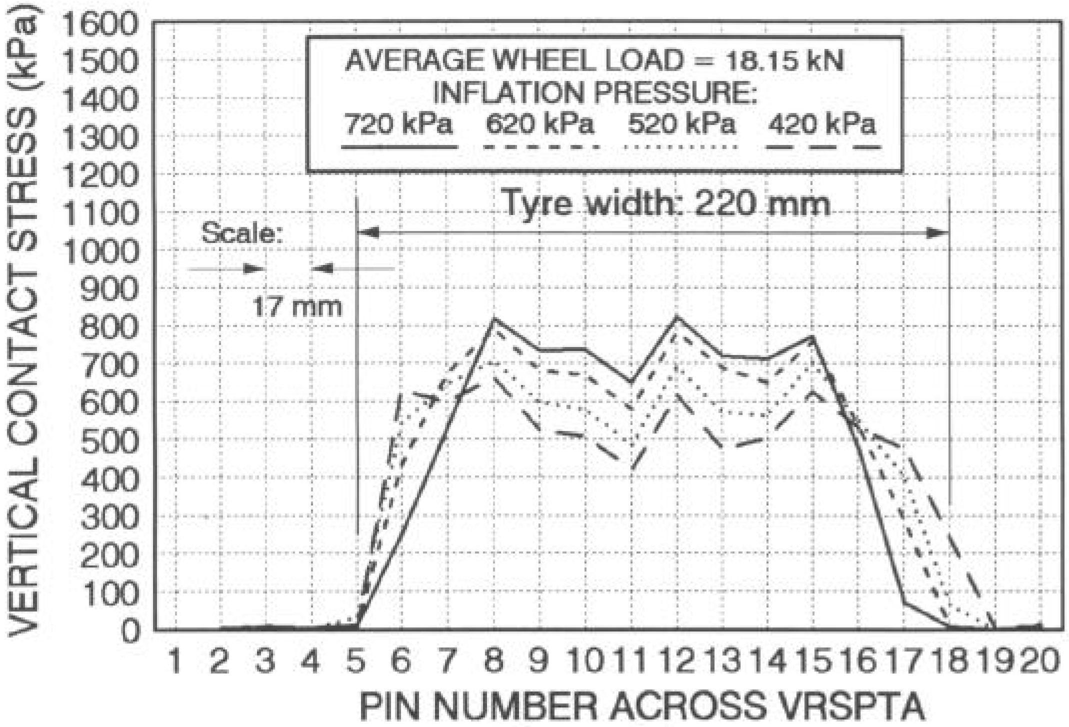


Figure 11

Maximum vertical contact stress across the smooth tyre at various inflation pressures at a constant load (18 kN)

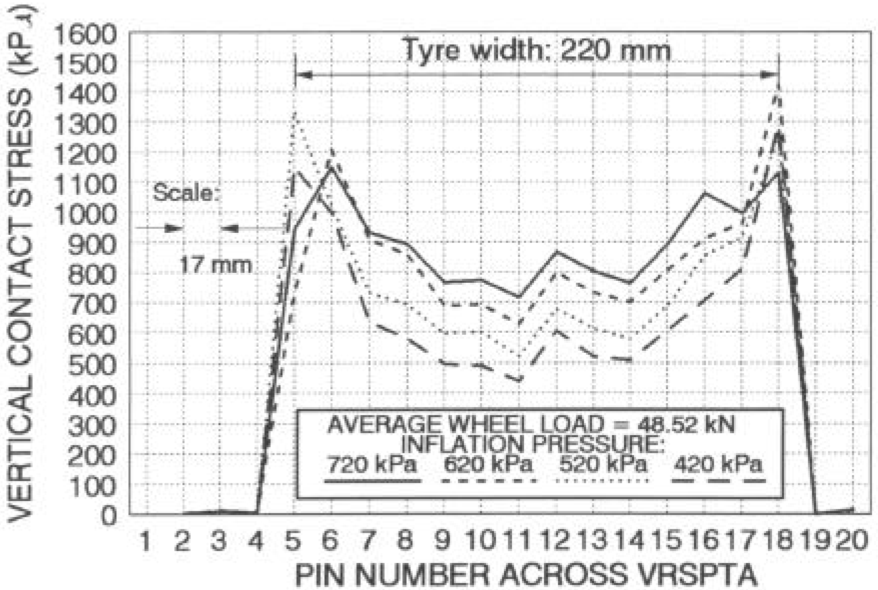


Figure 12

Maximum vertical contact stress across the smooth tyre at various inflation pressures at a constant load (48 kN)

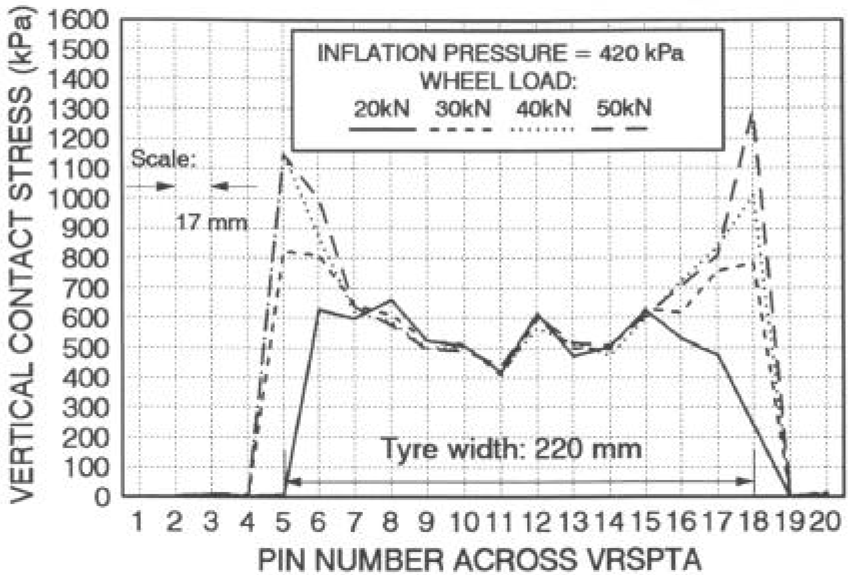


Figure 13

Maximum vertical contact stress across the smooth tyre at various loads at a constant inflation pressure (420 kPa)

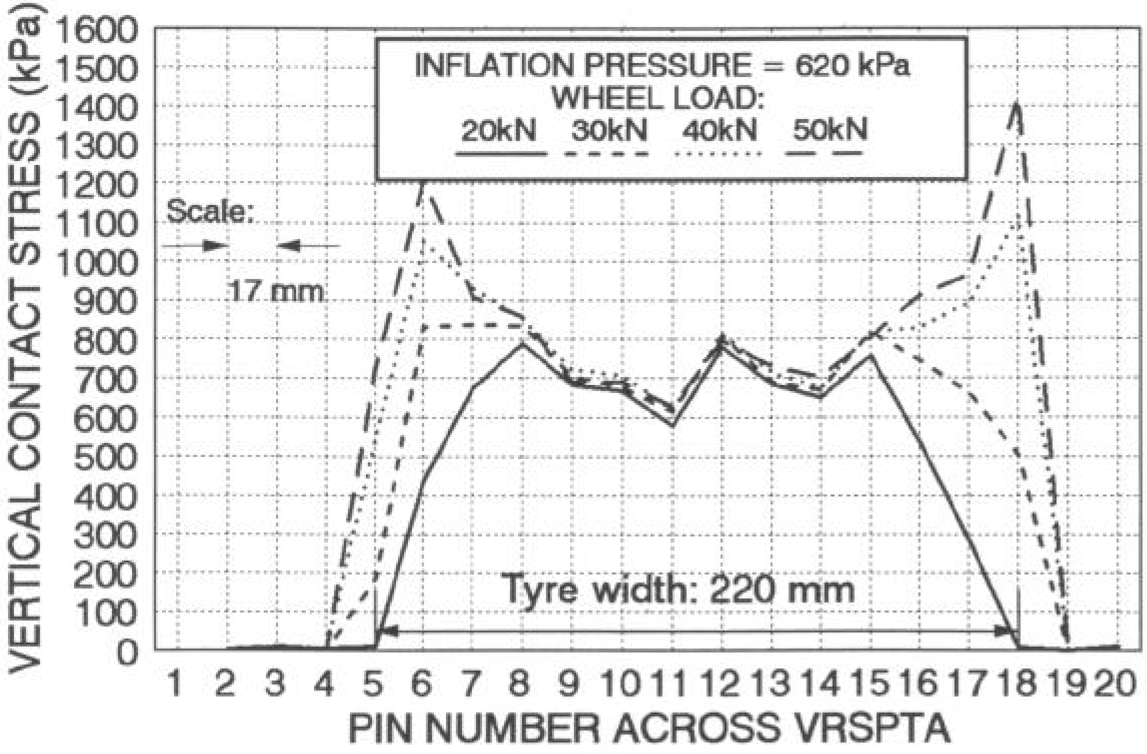


Figure 14
Maximum vertical contact stress across the smooth tyre
at various loads at a constant inflation pressure (620 kPa)

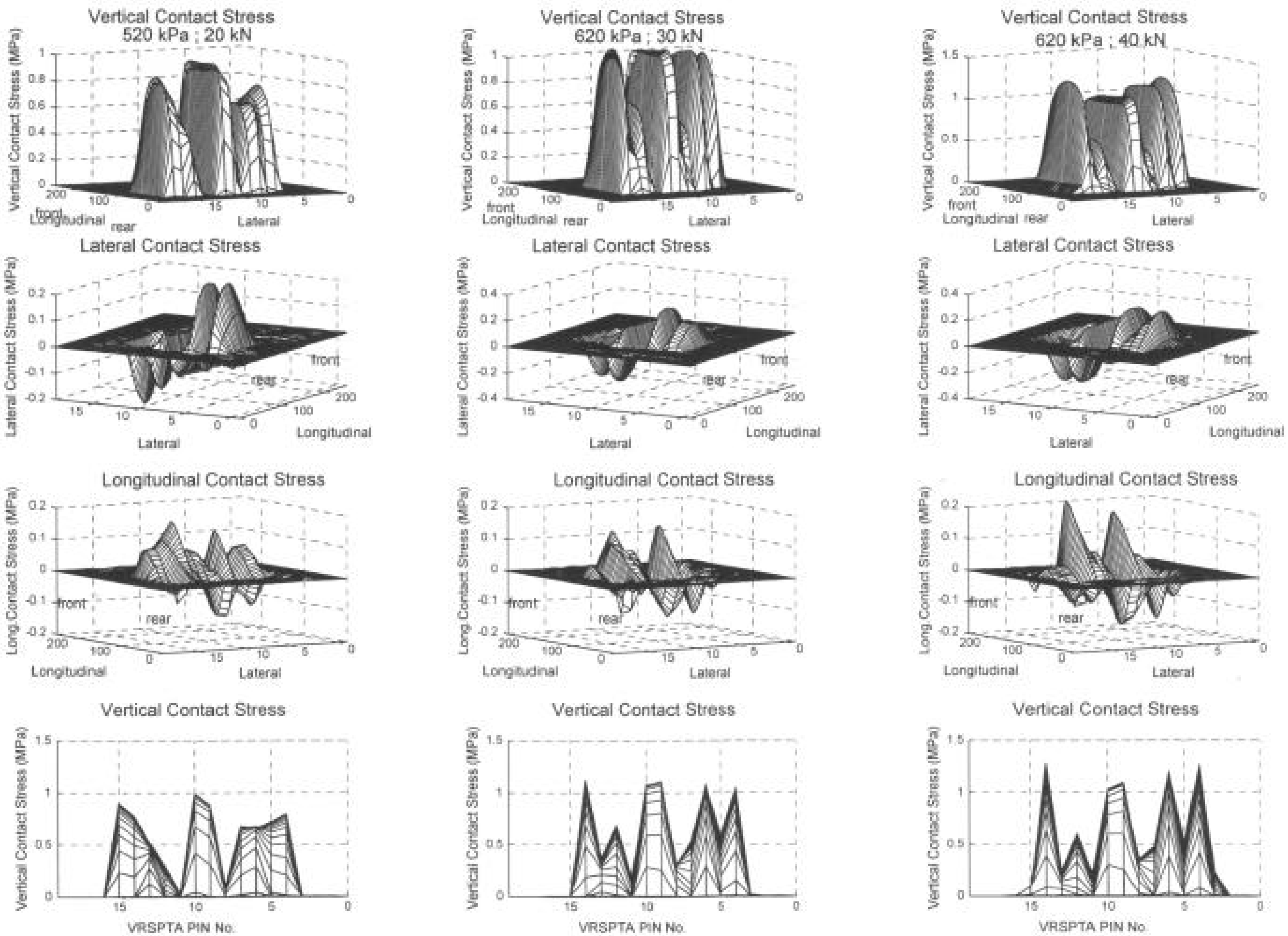


Figure 15: Graphic illustrations of typical contact stress distributions of a slow mowing (2 km/h) single bias/cross ply HVS tyre with tread grooves at various inflation pressure and load levels: Tyre TYPE II, Table 1

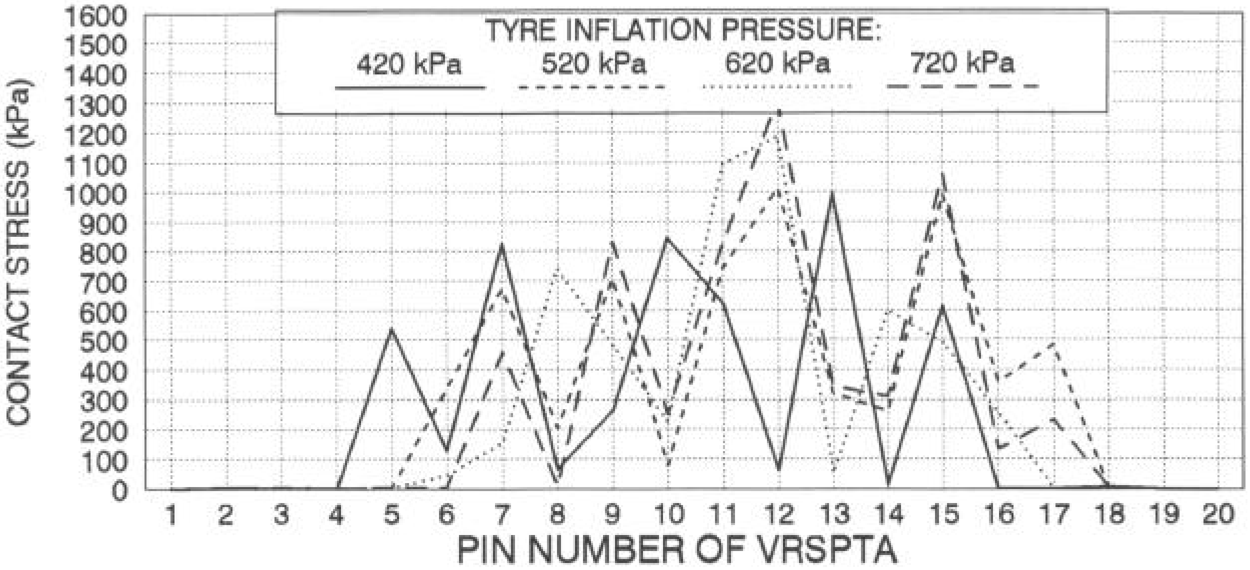


Figure 16

Maximum vertical contact stress across the HVS tyre with tread grooves at a constant load of of 20 kN and variable inflation pressure (Tyre Type II, Table 1, 11.00 x 20 14 ply)

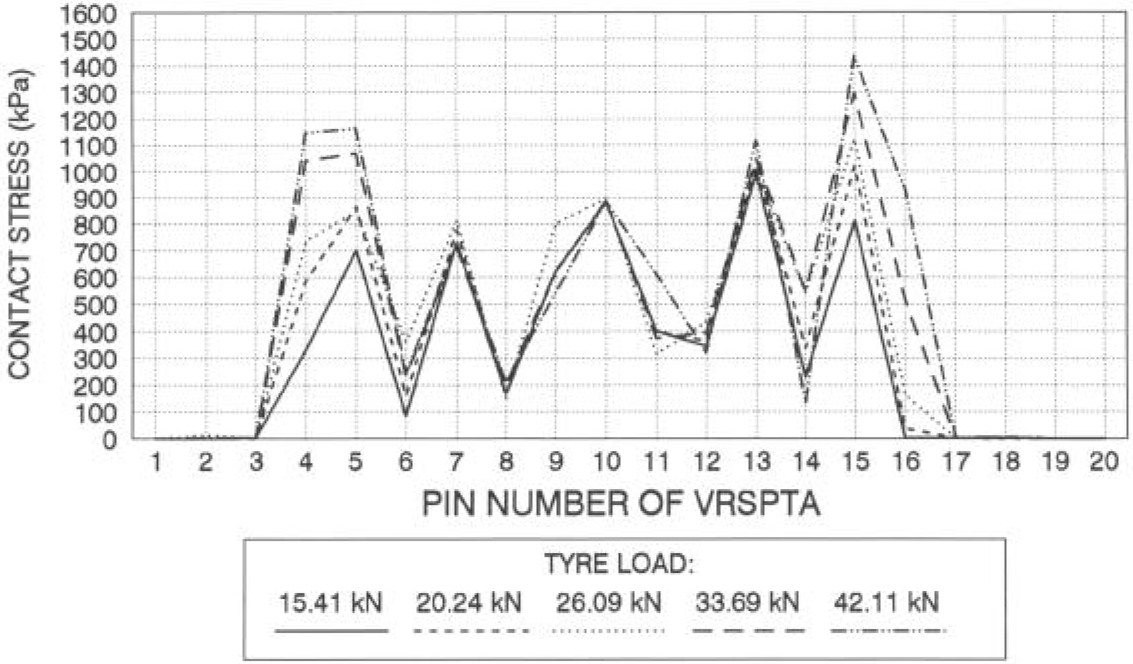


Figure 17
Maximum vertical contact stress across the HVS tyre with tread grooves at a constant inflation of 520 kPa and variable load
(Tyre Type II, Table 1, 11.00 x 20 14 ply)

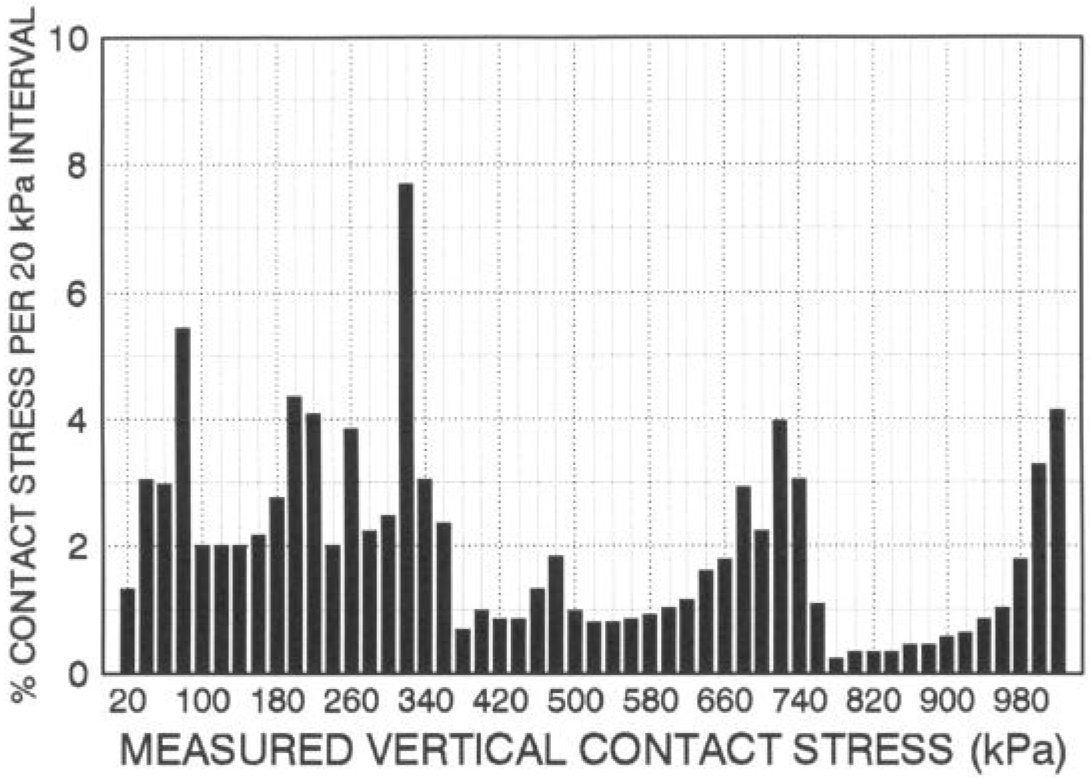


Figure 18

Bar chart of the verical contact stress distribution at 20 kPa intervals of the bias/cross-ply HVS tyre with tread grooves (17 kN; 520 kPa) (Tyre Type II, Table 1, 11.00 x 20 14 ply)

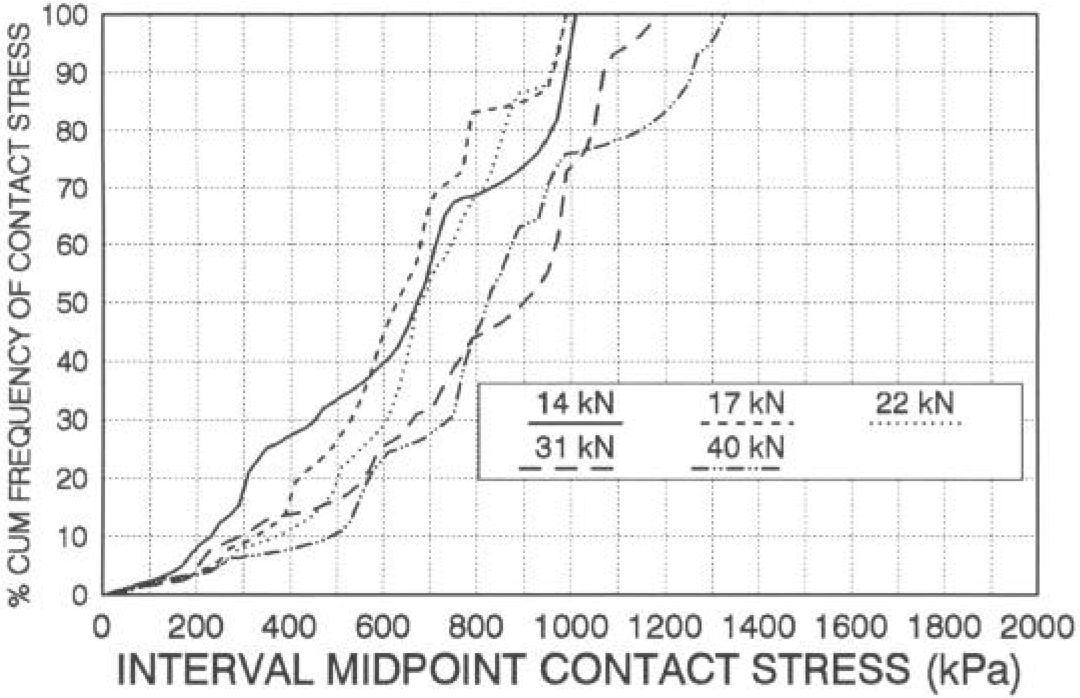


Figure 19
Percentage cumulative frequency of the bias/cross-ply HVS tyre at a load range: 14 kN to 40 kN, 520 kPa (Tyre Type II, Table 1, 11.00 x 20 14 ply)

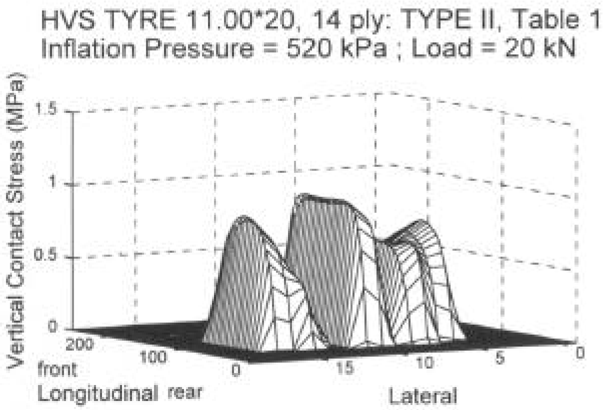


Figure 20a: Vertical Contact Stress

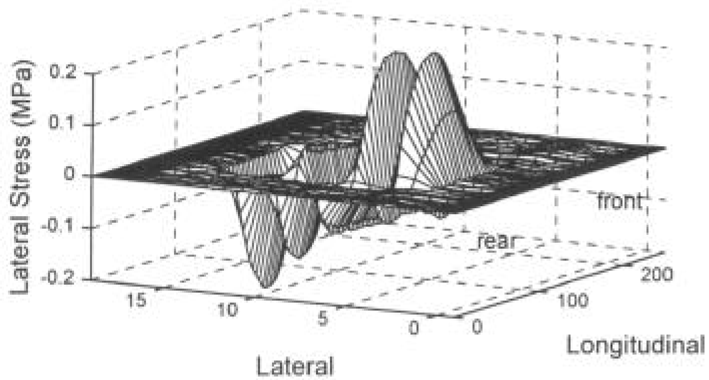


Figure 20b: Lateral Contact Stress

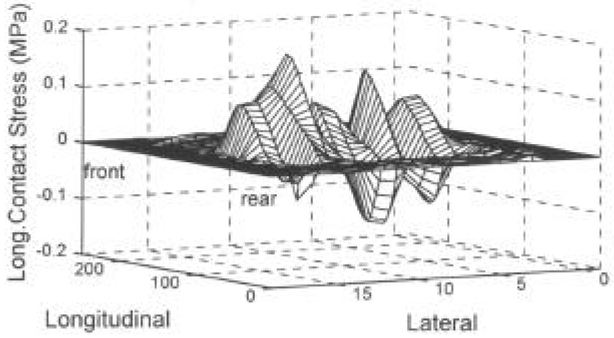


Figure 20c: Longitudinal Contact Stress

Figure 20a,b and c: 3-D Contact stresses of the HVS tyre at rated load

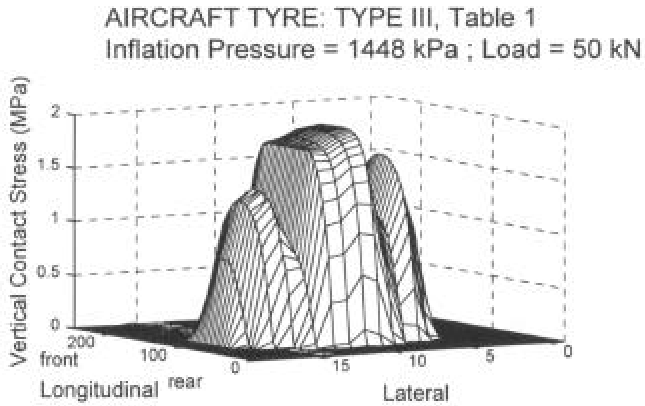


Figure 21a: Vertical Contact Stress

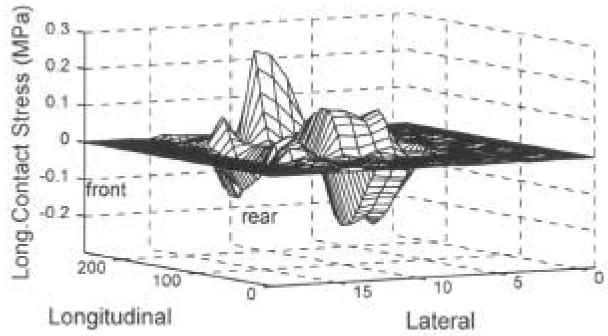


Figure 21c: Longitudinal Contact Stress

Figure 21a,b and c: 3-D Contact stresses of an Aircraft tyre

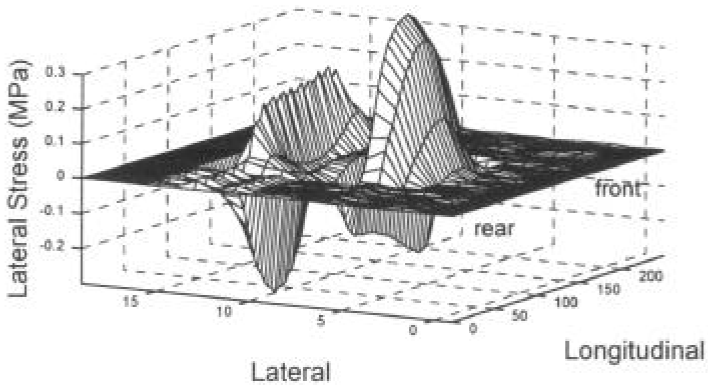


Figure 21b: Lateral Contact Stress

315/80 R22.5: TYPE IV, Table 1
Inflation Pressure = 800 kPa ; Load = 40 kN

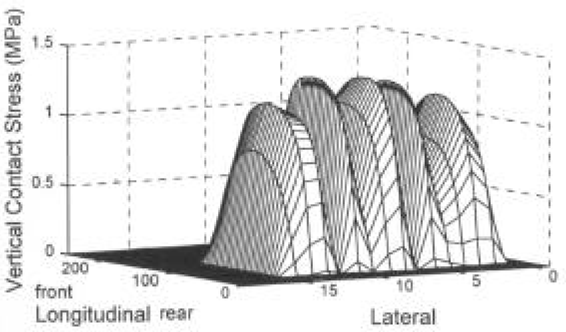


Figure 22a: Vertical Contact Stress

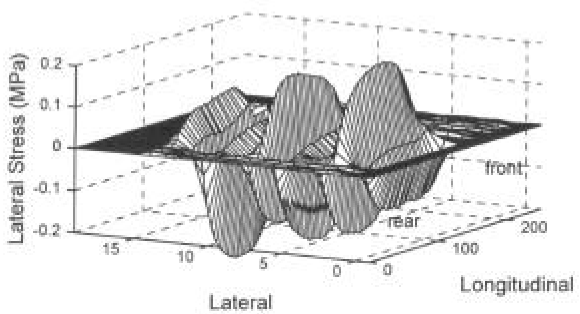


Figure 22b: Lateral Contact Stress

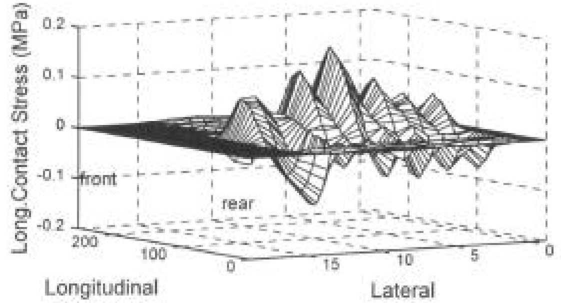


Figure 22c: Longitudinal Contact Stress

Figure 22a,b and c: 3-D Contact stresses of a 315/80 R22.5 tyre at rated load

425/65 R22.5: TYPE V, Table 1
Inflation Pressure = 900 kPa ; Load = 100 kN

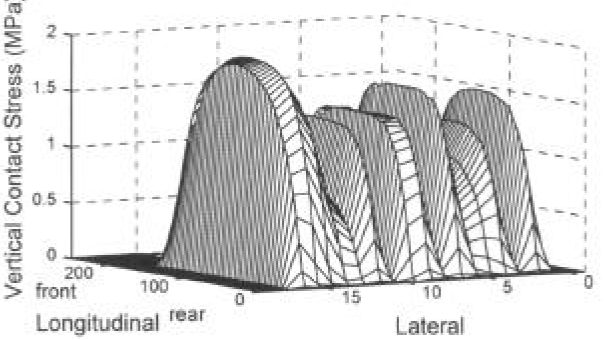


Figure 23a: Vertical Contact Stress

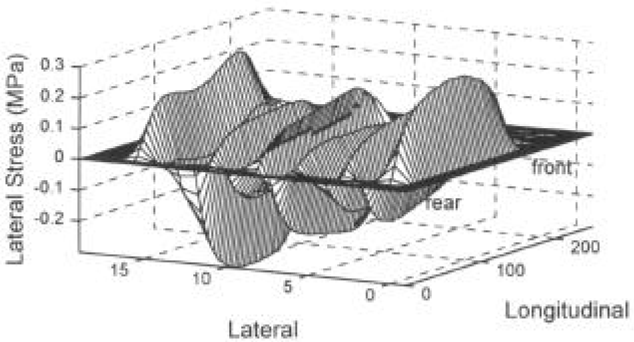


Figure 23b: Lateral Contact Stress

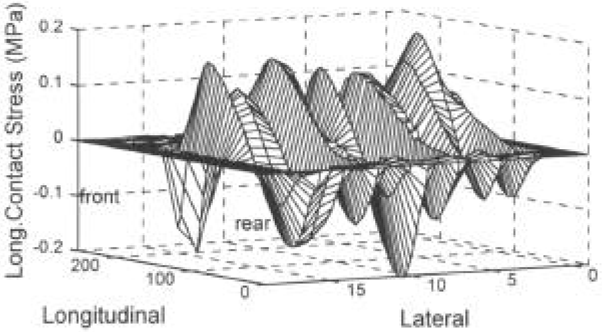


Figure 23c: Longitudinal Contact Stress

Figure 23a,b and c: 3-D Contact stresses of an overloaded wide base tyre

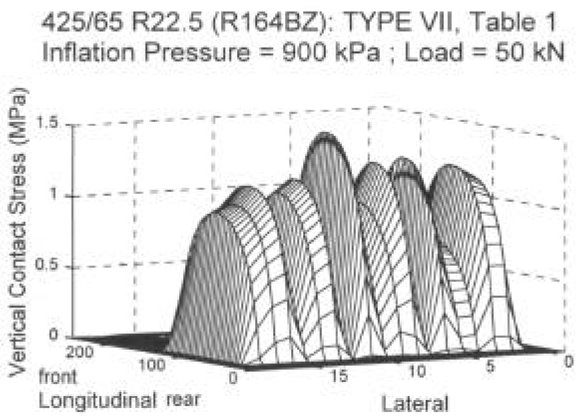


Figure 24a: Vertical Contact Stress

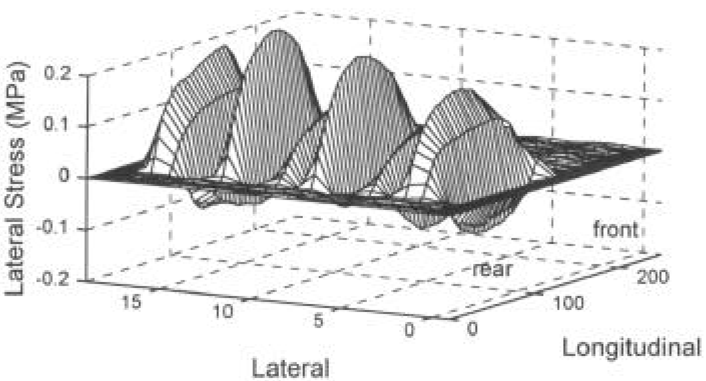


Figure 24b: Lateral Contact Stress

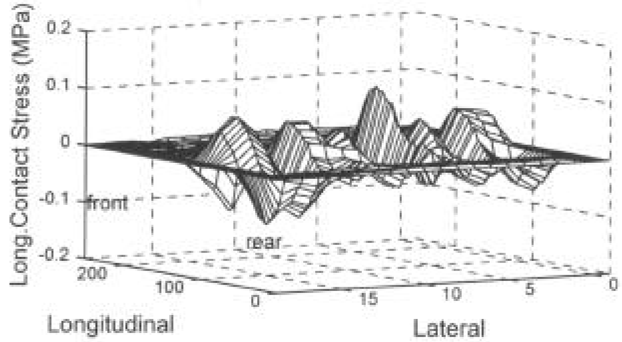
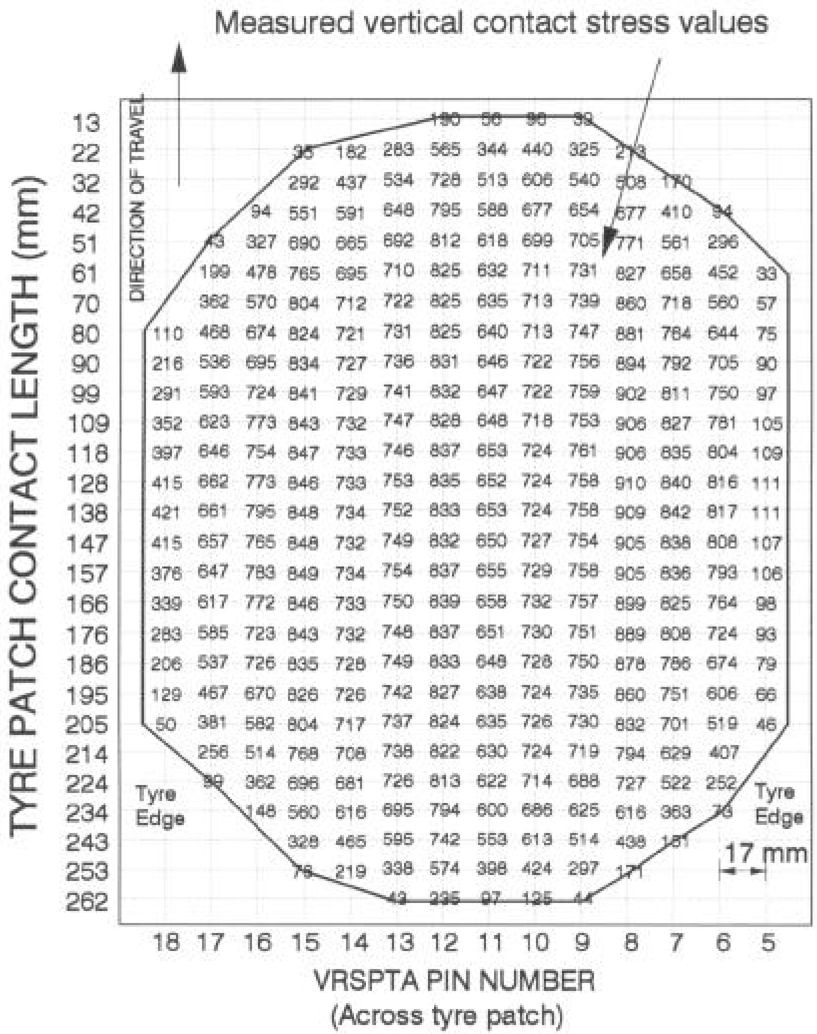


Figure 24c: Longitudinal Contact Stress

Figure 24a,b and c: 3-D Contact stresses of a wide base tyre at rated load



Patch area = 74 028 mm²

Figure 25d

VRSPTA measured contact area ("imprint") of the smooth tyre (TYPE I, Table 1) (Load = 27.38 kN; Inflation pressure = 720 kPa).

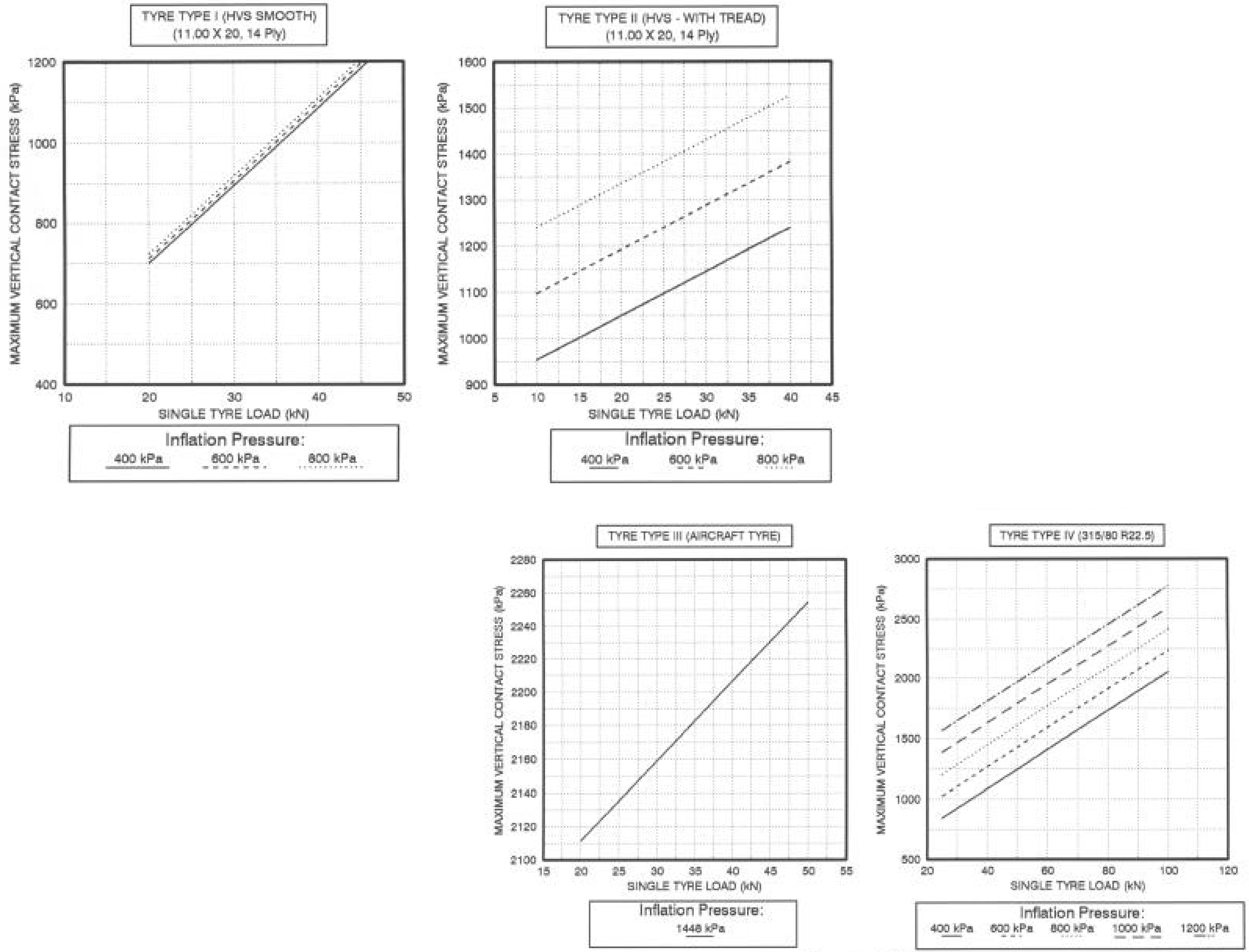
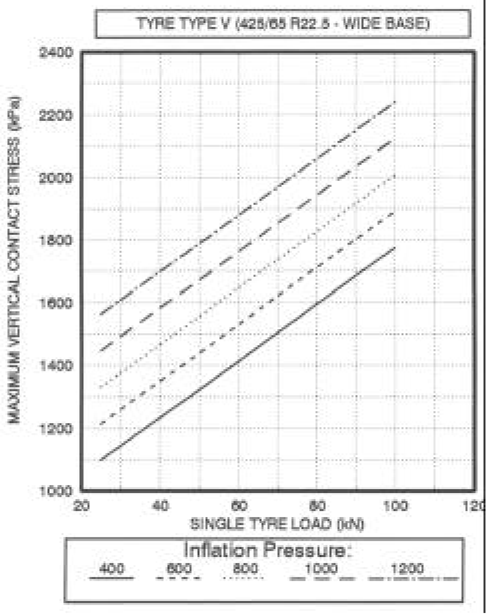
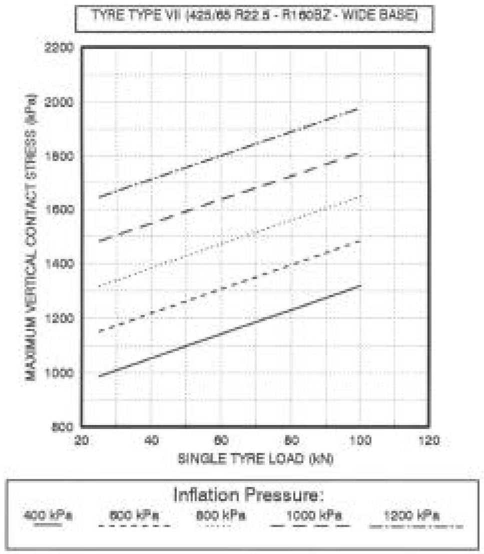


Figure 26

Relationships between tyre load and maximum vertical contact stress at various inflation pressures for tyre Types I,II,III and IV (Table 1)





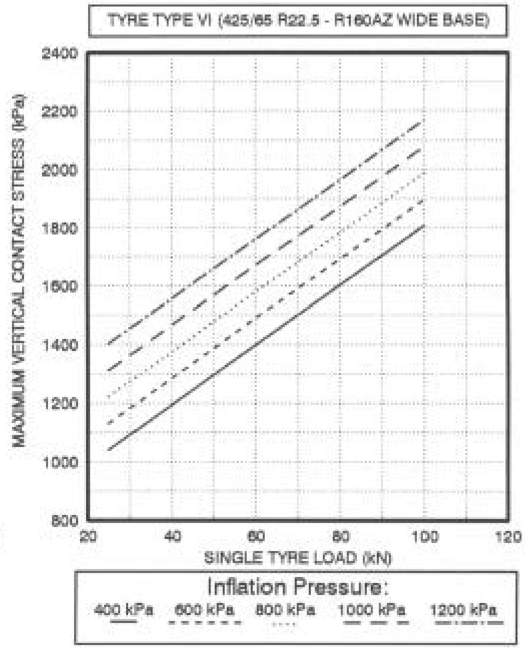
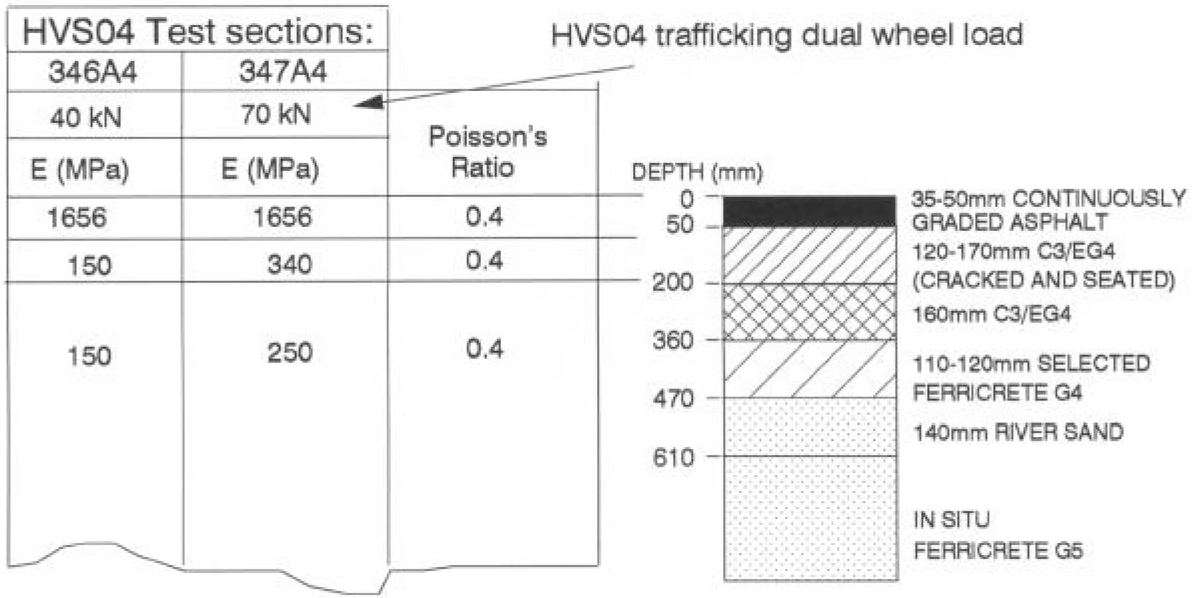


Figure 27
Relationships between tyre load and maximum vertical contact stress at various inflation pressures for tyre Types V,VI and VII (Table 1)



NS: Material codes according to TRH4 (1996), (Steyn et al, 1996)

Figure 28

Pavement structures evaluated with the HVS and used in this analysis (HVS04 Test Sections 346A4 and 347A4)

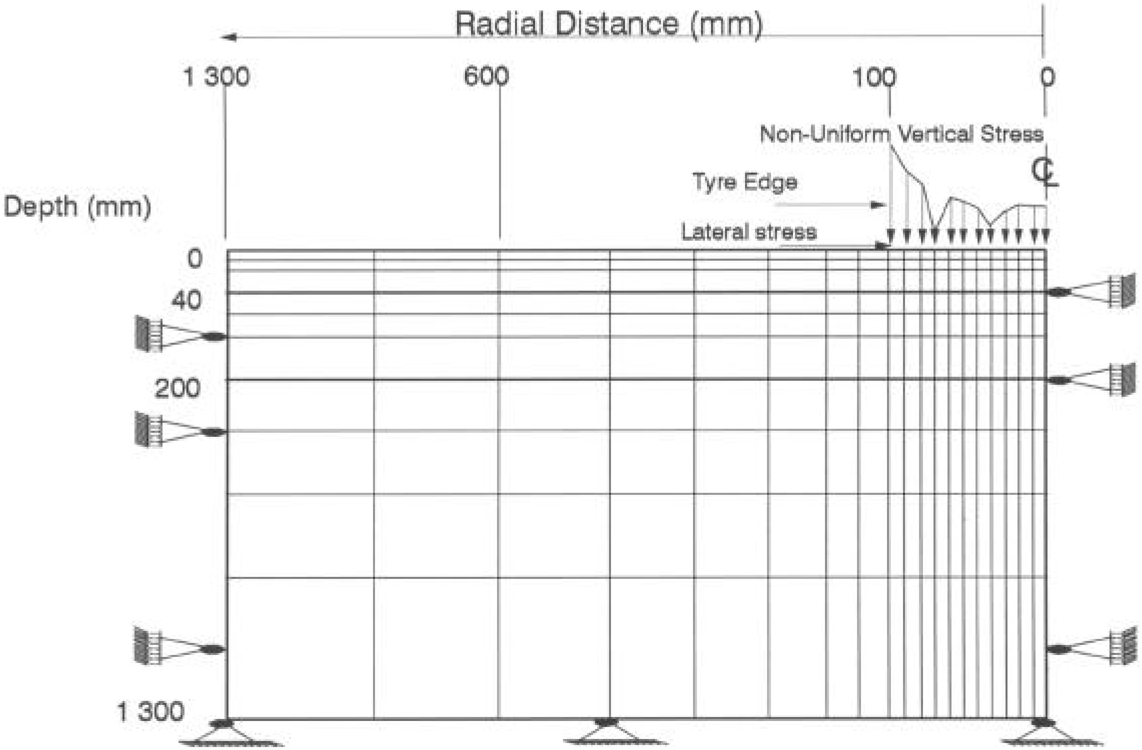


Figure 29
Axi-symmetrical Finite Element Model used in this study

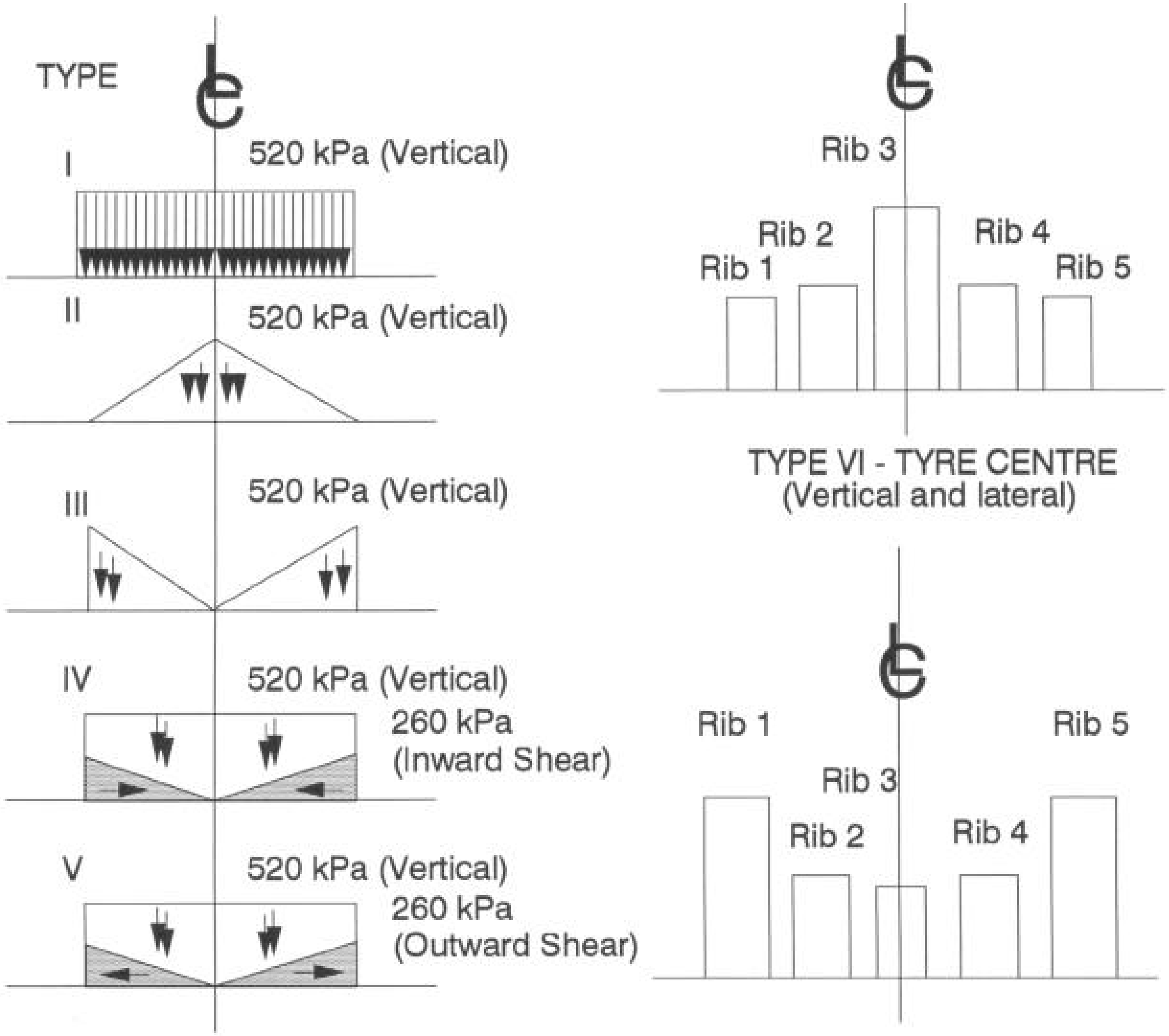


Figure 30
Load/Contact Stress Idealizations used
for the analysis in this study
(See also Table 6)

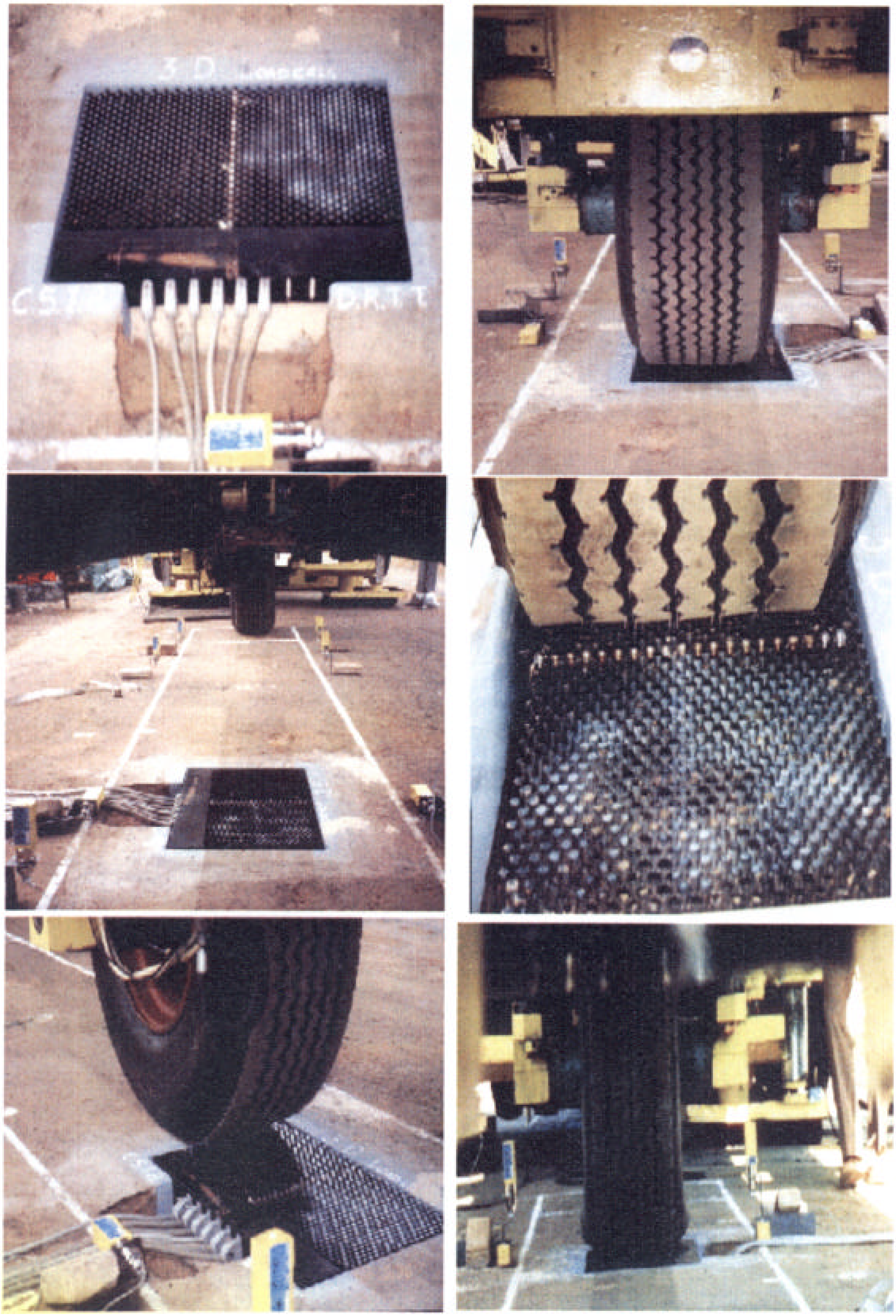


Plate 1 : Images of the Vehicle-Road Surface Pressure Transducer Array (VRSPTA) as used under the Heavy Vehicle Simulator (HVS). The tyre tested here is a wide base 425/65 R22.5 type.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