

Improved Performance Evaluation of Road Pavements by Using Measured Tyre Loading

J W MAINA* and M DE BEER

*CSIR Built Environment, PO Box 395, Pretoria, 0001

Email: JMaina@csir.co.za

Reference: CPA-0033

Abstract

South Africa is experiencing considerable growth in both passenger and freight traffic volumes because of increased economic activities. The Fourth annual State of Logistics Survey for South Africa indicated that total land transport in SA accounted for 1,5 billion tonnes, with recent growth of higher than 5 per cent, mainly captured by the road transport sector (CSIR, 2007). By supporting movement of people and goods, access to education and training, employment and health care, a sound road network plays a key role in socio-economic development of a country. In order to better understand impact of the increased loading on transport infrastructures, studies on tyre-road interaction in road pavement design have gained prominence in recent years. Tyres form an essential interface between vehicles and road pavement surfaces. These are the only parts of the vehicle that are in contact with the road and transmit the vehicle loading to the road surface. By using fewer tyres and carrying heavier cargo, modern trucks are exerting much higher contact stresses on the road surface than their predecessors. A good understanding of tyre-road contact stresses is, therefore, important for better road pavement designs, and hence performance. The aim of this paper is, amongst others, to inform on, and compare effects of tyre-road pavement contact stresses from two main types of truck tyres – the recently introduced single tyre (wide base) and the conventional dual truck tyres – on road pavement performance based on Strain Energy of Distortion.

KEY WORDS: Road Pavement, Tyres, Stress-In-Motion (SIM), Strain Energy of Distortion (SED), Multi-layer Linear Elastic Analysis.

1. General introduction

South Africa (SA), is a developing country with a total of approximately 750 000 km of roads, of which only 20 percent is currently paved. There are approximately 253 000 registered heavy vehicles (HVs) with a Total Vehicle (Combination) Mass (TVM/TCM) greater than 3.5 tonnes, of which 26 000 are buses (Bosman, 2004). The Fourth annual State of Logistics Survey for SA (CSIR, 2007) indicated that total land transport in SA accounted for 1,5 billion tonnes, with recent growth of higher than 5 per cent, mainly captured by the road transport sector, as opposed to the rail sector carrying only 0.2 billion tonnes. See **Figure 1**.

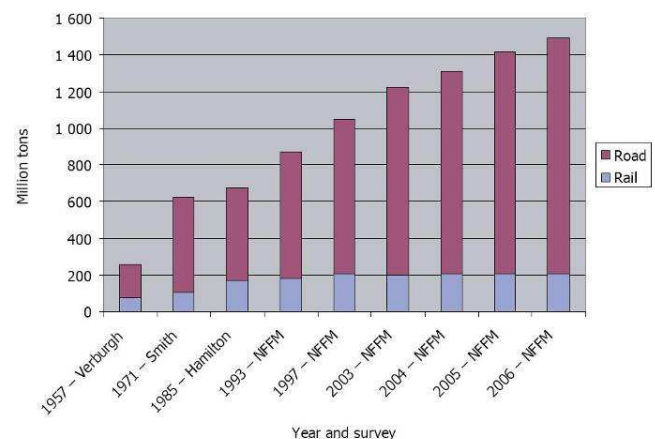


Figure 1. Historical Freight Transport Data (CSIR, 2007)

2. Quality and Importance of road Infrastructure in SA

Increased economic activities in SA have resulted in considerable growth in both passenger and freight traffic volumes and exposed serious shortcomings of the current South African Pavement Design Method (SAPDM). *Note The*

terms “road” and “pavement” are used interchangeably in this article, *excluding* “sidewalks”) The SA provincial and municipal road network has deteriorated to a state of almost disrepair. In 2007, the SA Institute of Civil Engineers (SAICE) produced an infrastructure scorecard in which a grading of between D (poor) and E (very poor) was allocated to the bulk of the road network (SAICE, 2006). Daily, newspapers carry articles on potholes and other road shortcomings which cost motorists in excess of R200 billion a year (News24, 2008). It is not surprising that there have been numerous calls for extensive revision of important parts of the design method in order to cope with the new traffic realities, amongst other factors. Traffic volumes on our national highways are at all time highs, for example, N3 has already carried the equivalence of 20 years of traffic over the last two years. A sound road network is an essential ingredient of a country's socio-economic well-being. Once constructed or structurally rehabilitated, however, a road will gradually deteriorate as a result of the combined effects of traffic loading and environmental forces (e.g. rainfall, ultra-violet radiation, temperature). The rate of deterioration depends on the ability of the pavement structure to resist these forces. As road conditions worsen, not only do journeys take longer, but fuel is wasted, vehicles are damaged and the number of accidents increases. The costs to the economy of this invisible tax are huge.

3. Trucks on our road infrastructure

As stated earlier, in SA the total length of roads is approximately 750 000 km, of which only 20 percent is currently paved. With approximately 253 000 registered HVs at a TVM/TCM greater than 3.5 tonnes (26 000 are buses), there is a move towards classifying South African roads according to the usage and composition of HVs. For this, Bosman (2005) defined three road classes, viz: Low, Medium and High, representing the traffic demand from HVs (based on 2 axle HVs), namely: Low HV roads (L-Roads), i.e. 2-axle HVs > 55 per cent; Medium HV roads (M-Roads), i.e. 35 per cent < 2-axle HVs ≤ 55 per cent. ; and High HV roads (H-Roads), i.e. 2-axle HVs ≤ 35 per cent. For example, the N3 National road, Truck Weigh-In-Motion (WIM) data indicated, that since 1988 there was an increase in medium 6- and 7-axle HVs at the expense of 4- and 5-axle HVs. A similar trend was observed for the heavier HVs, which showed a 50 per cent increase for 6-axle HVs and 100 per

cent increase for 7-axle HVs. In addition, based on the foregoing, estimated payloads in the N3 are the highest for 7-axle HVs, i.e. 18 tonnes (Bosman, 2005). Further, there was a huge increase in heavier HVs compared with the 1988 data and today almost 50 per cent of vehicles travelling on the N3 are HVs. In terms of growth in HVs on the toll portion of the road, the rate was approximately 8 per cent since 2002-2007, 20 per cent 2006-2007, and almost 40 per cent between February and October 2007. The N3 is therefore the national road with the highest growth and HV composition in SA (Le Roux, 2007).

4. Truck tyre loading and stresses

As pointed out earlier, tyres form an interface between vehicles and road pavement surfaces. These are the only part of the vehicles that are in contact with the road and, hence, transmit the vehicle loading to the road surface through a very small contact area, generally called the ‘contact patch’ or ‘tyre footprint’. By using fewer tyres and carrying heavier cargo, modern trucks are exerting much higher contact stresses on the road surface than their predecessors.

Currently, there are two main types of truck tyres widely used – the single (or so-called *wide base* tyre) and the conventional dual truck tyres – on our roads. A single wide base tyre, is a proportionately larger and more robust tyre that is now being used on trucks for heavy cargo, especially in Europe. This type of tyre is expected to replace dual tyres in the future, on condition of minimal damage to the existing road infrastructure. To be able to carry the same load as the dual tyres, the wide base tyre may have a much greater tyre inflation pressure and a larger individual “footprint” (but could also be with a smaller “footprint” than two standard dual tyres). Preliminary research studies have shown the single wide base tyre to be potentially much more damaging to certain types of road pavements – which may be a risk to road owners, and needs to be addressed more scientifically. A good understanding of tyre-road contact stresses is, therefore, important for better road pavement designs, durability and hence it's overall structural performance.

5. Stress-In-Motion (SIM) Technology

From a road pavement design point of view, pavement engineers are faced with many challenges, one of which is to utilize mechanistic-empirical pavement design methodologies in order

to optimize road structure design, construction and maintenance (McGee, 1999; Theyse *et al*, 2007). In general, there is a move away from the Equivalent Standard Axle Load (ESAL) concept towards using the full axle load spectra for design, which is considered a major step forward. In this paper, however, a new locally developed technique whereby individual multi-dimensional (3D) tyre-road contact forces (and hence actual contact stresses) are measured is also discussed. The technology is referred to as Stress-In-Motion (SIM) [which may be seen as a next generation of the well known Weigh-In-Motion (WIM) axle/truck weigh technologies, De Beer, 2007; Morgan *et al*, 2007], with specific use in capturing *individual* tyre loads and 3D contact stresses for the sole purpose of improved mechanistic-empirical road pavement design and analysis. The output, of which could potentially be used by consultants, road authorities and road managers to enhance optimization of existing and new road infrastructure design, construction, maintenance and its durability over the long term.

As a demonstration of SIM technology, tyre-road contact stress measurements were carried out on a busy national road (N3) in SA from the port of Durban to the inland province of Gauteng in 2003 (De Beer *et al*, 2004). The three-dimensional (3D) tyre-pavement loading and contact stress regimes of 45 165 individual tyres were measured using the SIM system that was developed by the CSIR Transport Infrastructure Engineering Group here in SA. This measurement series was performed at slow (< 5 km/hr) speed conditions at a controlled weigh-bridge point as part of the N3 Traffic Control Centre (N3-TCC) operations near Heidelberg in SA. In the 2003 study, the SIM system compared favourably with WIM scales covering TVM/TCM of 2 292 HVs; Individual tyre mass weights (45 165 tyres); typical tyre inflation pressures on HVs (1070 tyres) (De Beer, 2007). Suggestion for enhanced mechanistic-empirical pavement design, based on the concept for Strain Energy of Distortion (SED) as an indication and quantification parameter for *road damage* was presented, and is also discussed later in this paper. Typical distributions of individual tyre loading and inflation pressure data are given in **Figures 2 and 3**. Figure 3 indicate tyre loading ranging from 0.05 tonnes to 4.55 tonnes, and with steering tyres carrying approximately 1.2 tonnes higher for the N3 data set. The tyre inflation pressure change since 1974 is illustrated in **Figure 4**, showing an increasing trend from median values changing from 650 kPa to 800 kPa, with maximum

values towards 1100 kPa. Note that the current design standard tyre inflation pressure in SA is officially at 520 kPa. **Figures 4 and 5** illustrate typical tyre load/SIM configurations during measurement under the Heavy Vehicle Simulator (HVS) testing as well as on the N3 in 2003, with a real truck. With this type of improved data the SIM measurements can be used as input data for mechanistic analysis by General Analysis for Multi-layered Elastic Systems (GAMES) software for *pavement damage* studies in terms potential for fatigue failure (top-down cracking) or permanent deformation (rutting).

6. Typical Stress-In-Motion (SIM) Data

Typical vertical contact stress (Z) profiles of a single tyre tested under the HVS on the SIM system are illustrated in **Figure 6**. The data in the figure shows the well known changing of cross sectional shape of the vertical stress profiles from typical “n-shape” to “m-shape” at the higher loading, and lower inflation pressure conditions. For example, compare the data at the bottom right (15 kN @ 800 kPa) showing a typical n-shape vertical (Z) stress distribution to the left upper corner case (50 kN @ 520 kPa), which is a typical m-shape vertical (Z) stress distribution. Similar results for the lateral (Y) and longitudinal (X), contact stresses were obtained simultaneously with the SIM system but is not presented here (see De Beer *et al*, 1997, 2007, 2008). The foregoing is officially referred to as tyre “*finger printing*” which enable a much improved tyre model for road design purposes compared to the simplified (traditional) circular uniform pressure shape that is currently still in use. The vertical (Z) stress tyre loading conditions applied during the recent Hot Mix Asphalt (HMA) overlay testing [supported by Gauteng Department of Public Works and Roads (GDPTWR) and the South African Bitumen Association (SABITA)] are shown in **Figures 8 and 9**. Typical plastic deformation results associated with n- and m-shape applied stresses (i.e. rutting under HVS testing) are shown in **Figures 7, 10 and 11**.

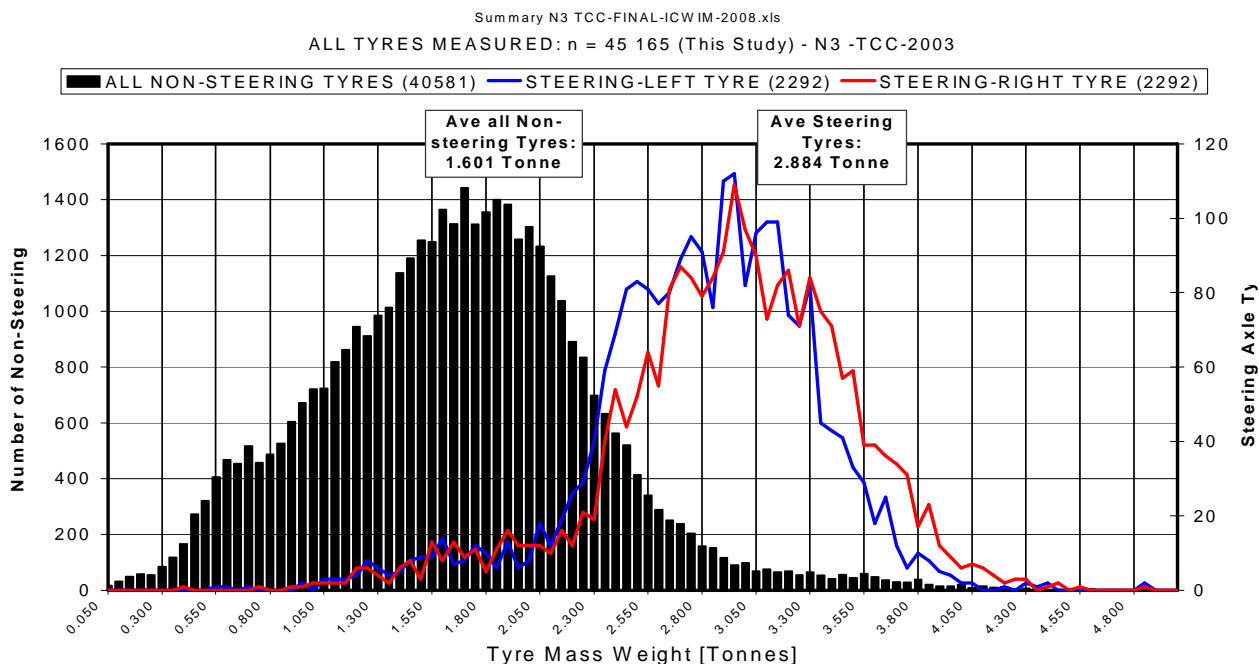


Figure 2. Typical distributions (from SIM) in tyre Mass Weights in 2003 on the N3 North bound, showing also a difference of approximately 1.2 tonne heavier loading on the steering tyres.

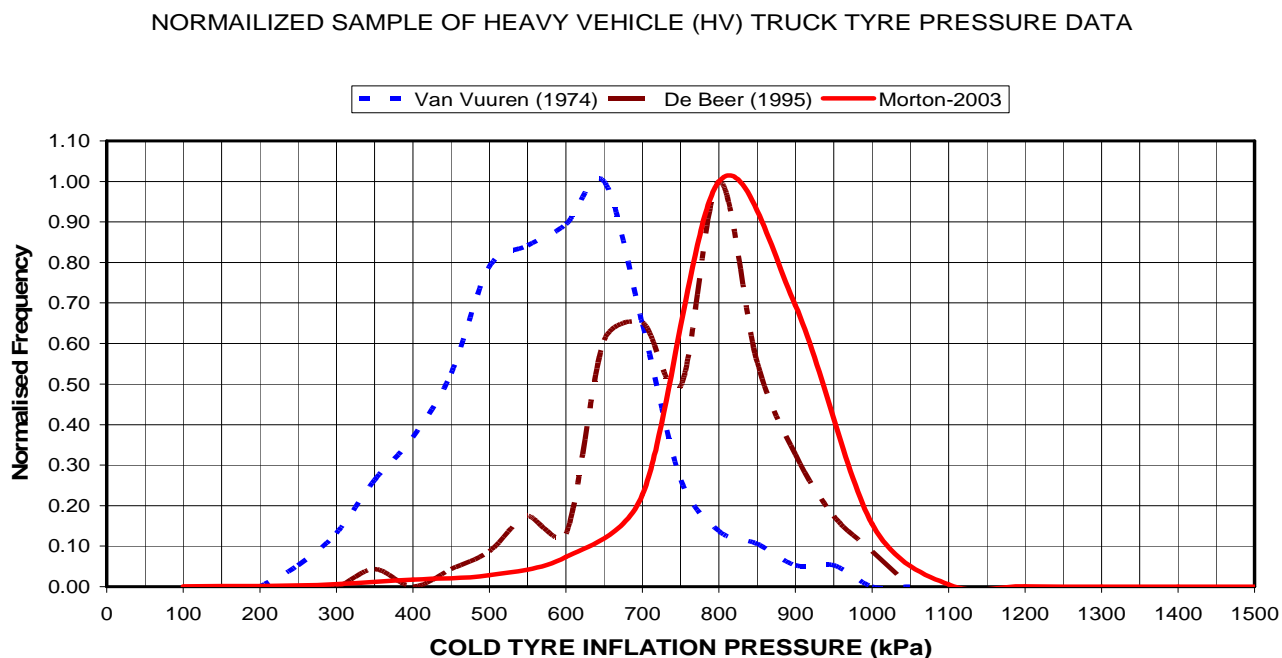


Figure 3. Some historical tyre Inflation pressure data of Heavy Vehicles since 1974. Note the increase in inflation pressure of truck tyres since 1974, which is almost 20 per cent over 20 years.



Figure 4. Dual Pad SIM system under Heavy Vehicle Simulator (HVS) tyre testing



Figure 5. Typical heavy vehicle moving slowly over the 4 Pad SIM system at the N3-TCC.

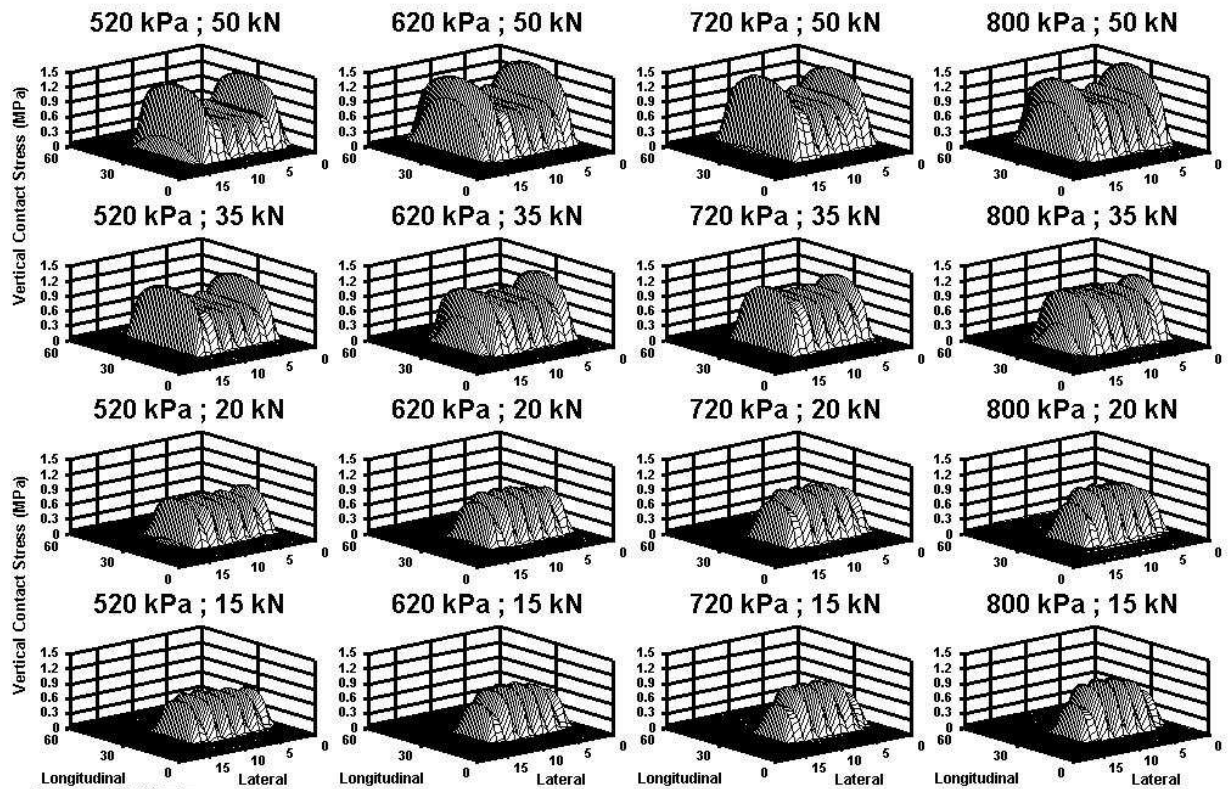


Figure 6. Vertical tyre pavement contact stress profiles of a single 11R22.5 tyre (HVS) over a range of tyre loading (15 kN to 50 kN) on Y-axis and inflation pressures (520 kPa to 800 kPa) on X-axis.



Figure 7. HVS test section showing some rutting (plastic deformation) in the HMA overlay after recent channelised testing with 11R22.5 dual tyres at a road surface temperature of 60 °C.

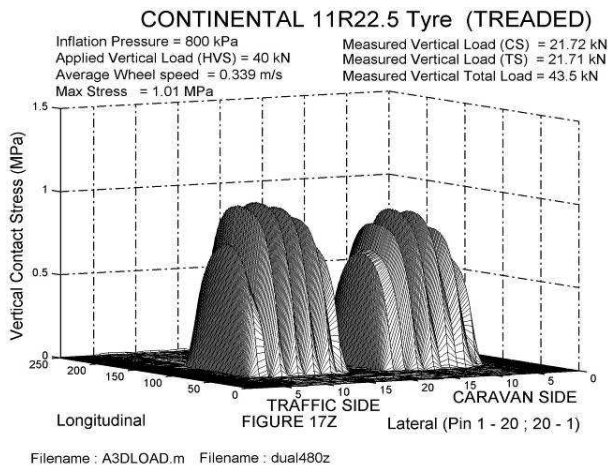


Figure 8. Typical vertical contact stress (Z) distribution (n-shape) of the 11R22.5 dual HVS tyres at a loading of 40 kN and 800 kPa Inflation pressure

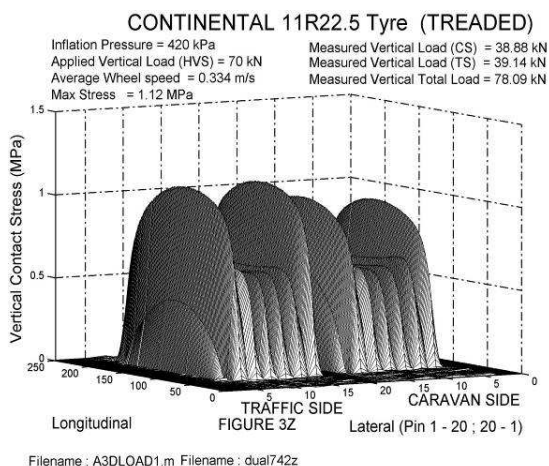


Figure 9. Typical vertical contact stress (Z) distribution (m-shape) of the 11R22.5 dual HVS tyres at a loading of 60 kN and 420 kPa Inflation pressure.

7. Equations for Mechanistic Road Analysis

The key to proper design of road pavements and their subsequent maintenance is the ability to understand the macroscopic behaviour of materials when subjected to traffic loading under varying environmental conditions. Development of analytical (closed-form solution) methods for resilient response of pavements may be traced



Figure 10. Typical rutting under one tyre in the HMA overlay after HVS testing in the channelised mode using 40 kN and 800 kPa Inflation pressure and 60 °C (n-shape- Dual tyre loading – see Figure 8).



Figure 11. Typical rutting under one tyre in the HMA overlay after HVS testing in channelised mode using 60 kN and 420 kPa Inflation pressure and 60 °C (m-shape- Dual tyre loading – see Figure 9).

back to the early 1940s, when Burmister expanded Boussinesq's linear elastic formulations of 1885 by utilizing stress and displacement equations of elasticity as derived by Love (1923) to satisfy the equations of equilibrium and compatibility (Boussinesq, 1885 and Burmister, 1943). Since then, numerous researchers have extended the method to cater for multiple number of layers and loads. The following assumptions ensure that the

analytical methods are mathematically exact (Huang, 2004):

- Each road pavement layer is homogeneous, isotropic and linearly elastic with an elastic modulus E and Poisson ratio, ν .
- Each road pavement layer has a finite thickness h , but the bottom layer is infinite.
- A uniformly distributed pressure q is applied on the surface over circular area of radius a .
- Continuity conditions are satisfied at the layer interfaces as indicated by the same vertical stress, shear stress, vertical displacement and radial displacement.

In order to develop mathematical relations to be used for analysis, the road pavement structure is considered to be a multi-layered system as shown in **Figure 12**. Cartesian coordinate system used (X, Y, Z) is a global coordinate system, while the coordinate system (x, y, z) is a local coordinate system. A circular load is assumed to act on the surface of the pavement as shown in **Figure 13**. Furthermore, by introducing a cylindrical coordinate system with a z -axis common to the local coordinate system and neglect body forces, the equilibrium equation in the (r, z, θ) for an infinitesimal element (**Figure 14**) can be expressed using Navier's equations as follows:

$$\begin{aligned}\nabla^2 u + \frac{1}{1-2\nu} \frac{\partial \Delta}{\partial r} - \frac{u}{r^2} - \frac{2}{r^2} \frac{\partial v}{\partial \theta} &= 0 \\ \nabla^2 v + \frac{1}{1-2\nu} \frac{\partial \Delta}{r \partial \theta} - \frac{v}{r^2} + \frac{2}{r^2} \frac{\partial u}{\partial \theta} &= 0 \dots\dots\dots(1) \\ \nabla^2 w + \frac{1}{1-2\nu} \frac{\partial \Delta}{\partial z} &= 0\end{aligned}$$

where

$$\nabla^2 = \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} - \frac{m^2}{r^2} + \frac{\partial^2}{\partial z^2} \right) \text{ and}$$

$$\Delta = \frac{\partial u}{\partial r} + \frac{u}{r} + \frac{1}{r} \frac{\partial v}{\partial \theta} + \frac{\partial w}{\partial z}$$

A unique solution to these equations may be obtained by introducing displacement functions, Φ and Ψ , that would satisfy the equilibrium equations and compatibility equations. This can be accomplished if the displacement functions are solutions of bi-harmonic and harmonic equations, respectively:

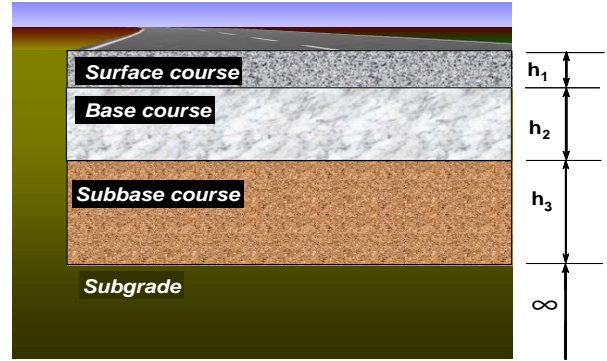


Figure 12. Typical multi-layered road pavement structure.

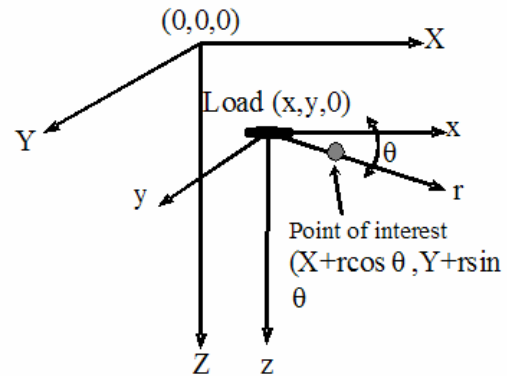


Figure 13. Global and local coordinates of tyre-road system.

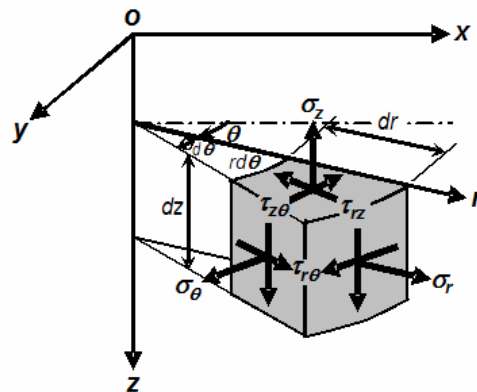


Figure 14. Infinitesimal element at equilibrium.

$$\begin{aligned}\nabla^4\Phi &= 0 \\ \nabla^2\Psi &= 0\end{aligned}\quad \dots\dots\dots(2)$$

The displacements may be expressed in terms of displacement functions as follows:

$$\begin{aligned}u &= -\frac{\partial^2\Phi}{\partial r\partial z} + \frac{2}{r}\frac{\partial\Psi}{\partial\theta} \\ v &= -\frac{\partial^2\Phi}{r\partial\theta\partial z} - \frac{2}{r}\frac{\partial\Psi}{\partial r} \quad \dots\dots\dots (3) \\ w &= 2(1-\nu)\nabla^2\Phi - \frac{\partial^2\Phi}{\partial z^2}\end{aligned}$$

Making use of strain-displacement and stress-strain relationships from Hooke's law, stresses may be expressed in terms of displacement functions as follows:

$$\left. \begin{aligned}\frac{\sigma_r}{G} &= \frac{\partial}{\partial z}\left(\nu\nabla^2\Phi - \frac{\partial^2\Phi}{\partial r^2}\right) + \frac{2}{r}\frac{\partial^2\Psi}{\partial\theta\partial r} - \frac{2}{r^2}\frac{\partial\Psi}{\partial\theta} \\ \frac{\sigma_\theta}{G} &= \frac{\partial}{\partial z}\left(\nu\nabla^2\Phi - \frac{1}{r}\frac{\partial\Phi}{\partial r} - \frac{1}{r^2}\frac{\partial^2\Phi}{\partial\theta^2}\right) - \frac{2}{r}\frac{\partial^2\Psi}{\partial\theta\partial r} + \frac{2}{r^2}\frac{\partial\Psi}{\partial\theta} \\ \frac{\sigma_z}{G} &= \frac{\partial}{\partial z}\left[(2-\nu)\nabla^2\Phi - \frac{\partial^2\Phi}{\partial z^2}\right] \\ \frac{\tau_{\theta z}}{G} &= \frac{\partial}{r\partial\theta}\left[(1-\nu)\nabla^2\Phi - \frac{\partial^2\Phi}{\partial z^2}\right] - \frac{\partial^2\Psi}{\partial r\partial z} \\ \frac{\tau_{zr}}{G} &= \frac{\partial}{\partial r}\left[(1-\nu)\nabla^2\Phi - \frac{\partial^2\Phi}{\partial z^2}\right] + \frac{\partial^2\Psi}{r\partial\theta\partial z} \\ \frac{\tau_{\theta r}}{G} &= \frac{\partial^2}{r\partial\theta\partial z}\left[\frac{\Phi}{r} - \frac{\partial\Phi}{\partial r}\right] - 2\frac{\partial^2\Psi}{\partial r^2} - \frac{\partial^2\Psi}{\partial z^2}\end{aligned}\right\} \quad (4)$$

where, for each particular layer of the pavement system, $G = \mu = \frac{E}{2(1+\nu)}$ is shear stress with E as elastic modulus of the material in the layer and ν is Poisson's ratio of the material.

Solutions for the displacement functions Φ and Ψ may be determined by using Hankel transform. Responses in terms of road pavement displacements, stresses and strains may then be obtained by using Hankel inverse transform together with road pavement boundary conditions

as explained in detail elsewhere (Maina and Matsui, 2004).

8. Analysis for Multiple Loading

In order to evaluate effect of tyre loading on pavement responses, measured SIM pin values were used as input load data for mechanistic analysis of road pavement analysis. This necessitated the use of multiple loads in the analysis. It is important to briefly explain the process followed in obtaining the total final results. Reference is again made to **Figure 13**, which shows positions of a tyre load with respect to global coordinate axis (X, Y, Z). For analysis of multiple loads, each loading is represented in local Cartesian axes (x, y, z) as well as cylindrical axes (r, θ , z) with their origins at the centre of the load as shown in **Figure 13**. Since cylindrical axes are used in the analysis, results at a particular analysis point for each load case have to be represented in a common global coordinate system. Because the assumptions listed in Section 7 hold, the principle of superposition may be utilized. Henceforth, results at each analysis point from each loading case, which are now represented in global Cartesian coordinate are summed up based on the in order to obtain the final results.

The relation between stresses in cylindrical coordinate (r, θ , z) axis and stresses in (x, y, z) can be presented as follows:

$$\begin{Bmatrix}\sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{xz} & \tau_{yz} & \sigma_z\end{Bmatrix} = [S]^T \begin{Bmatrix}\sigma_r & 0 & \tau_{rz} \\ 0 & \sigma_\theta & 0 \\ \tau_{rz} & 0 & \sigma_z\end{Bmatrix} [S] \quad \dots(5)$$

where

$$[S] = \begin{bmatrix}\cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1\end{bmatrix} \quad \dots\dots\dots(6)$$

assuming x-axis of local Cartesian coordinates is in the same direction as X-axis of the global Cartesian coordinates. Similar procedure is used for displacements and strains as well.

9. Strain Energy of Distortion (SED)

According to Timoshenko and Goodier (1951), the quantity of strain energy stored per unit volume of

the material can be used as a basis for determining the limiting stress at which failure occurs. For this, to be applied to isotropic materials, it is important to separate this energy into two parts; one due to the change in volume and the other due to the distortion, and consider only the second part in determining the strength. Whatever the stress system, failure occurs when the strain energy of distortion reaches a certain limit. Now, total strain energy per unit volume, V_0 , can be expressed by using Hooke's law as follows:

$$V_0 = \frac{1}{2E}(\sigma_x^2 + \sigma_y^2 + \sigma_z^2) - \frac{\nu}{E}(\sigma_x\sigma_y + \sigma_y\sigma_z + \sigma_z\sigma_x) + \frac{1}{2G}(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2) \quad \dots(7)$$

Whereas the component of strain energy due to distortion (SED), can then be expressed as follows:

$$SED = V_0 - \frac{1-2\nu}{6E}(\sigma_x + \sigma_y + \sigma_z)^2 \quad \dots\dots\dots(8)$$

It is the notion in this paper that with this approach, points within the pavement structural system that have higher values of strain energy of distortion (SED) (so-called “*hot-spots*”) will potentially fail first

before points with relatively lower values, as was also indicated by Perdomo and Nokes (1993) and De Beer *et al* (1997). Ideally, this should be linked with the formation of potholes.

10. Worked Examples and Analytical Results

To illustrate the above methodology a typical three-layer pavement structure was considered in this study with structural properties shown in **Table 1**. Mechanistic analysis of road pavement system was then carried out considering four sets of SIM measured data (two each from dual and single tyres for n- and m-shaped contact stresses) as shown in **Figures 15 (a)** and **(b)** and **Figures 16 (a)** and **(b)**.

Table 1 Three Layer Pavement Model (*this study*)

Layer	Thickness (cm)	Modulus (MPa)	Poisson's ratio
Surface and base course	15	3,500	0.44
Subbase course	15	350	0.35
Subgrade soil	∞	100	0.35

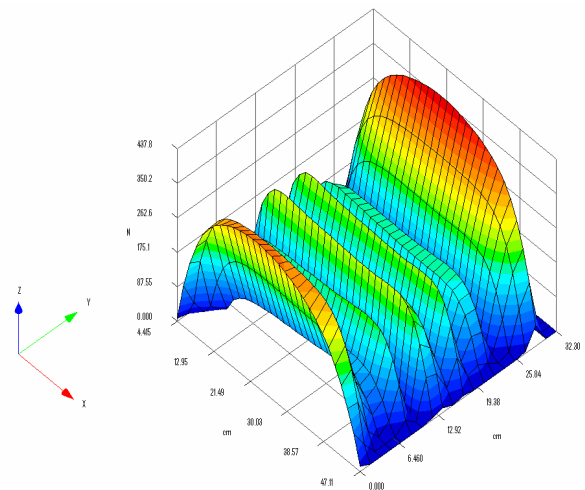
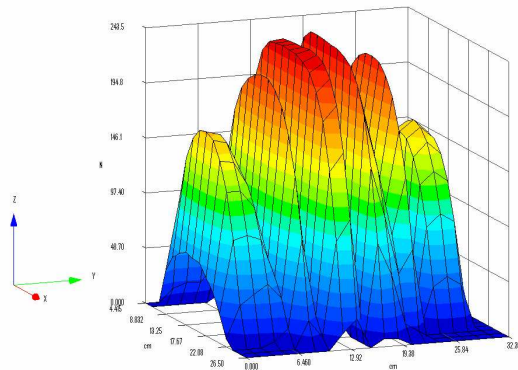


Figure 15. (a) Single tyre - n-shaped vertical contact stress and (b) m- shaped vertical contact stress

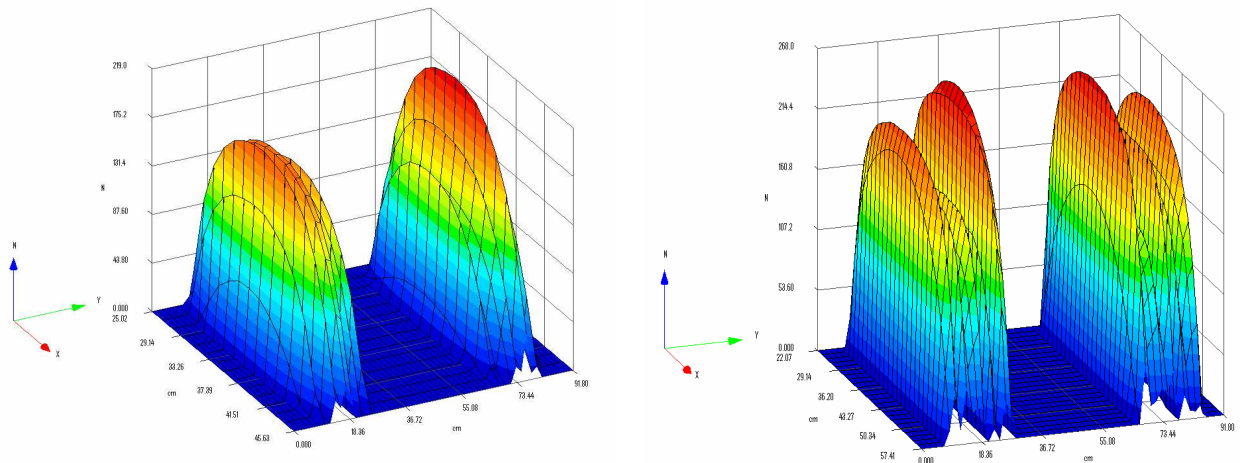


Figure 16. (a) Dual tyre - n-shaped vertical contact stress and (b) m-shaped vertical contact stress

Numerous computer analysis runs were carried out for the same pavement structure shown in **Table 1** in order to identify, if any, differences in pavement responses between (a) the two different types of tyre and (b) the two different types of contact stress distribution. Comparison was made based on the computed SEDs at various points on the road pavement structure. Since significantly high number of loads (3-dimensional measured SIM

data) and road pavement analysis points was considered, the CSIR's supercomputing resources (i.e. C4) were used to speed up the analysis time. The C4 system is located on the CSIR's Pretoria campus and has three cluster computers, namely opteron (with 196 central processing units, CPUs), xeon (with 102 CPUs) and itanium2 (with 70 CPUs).

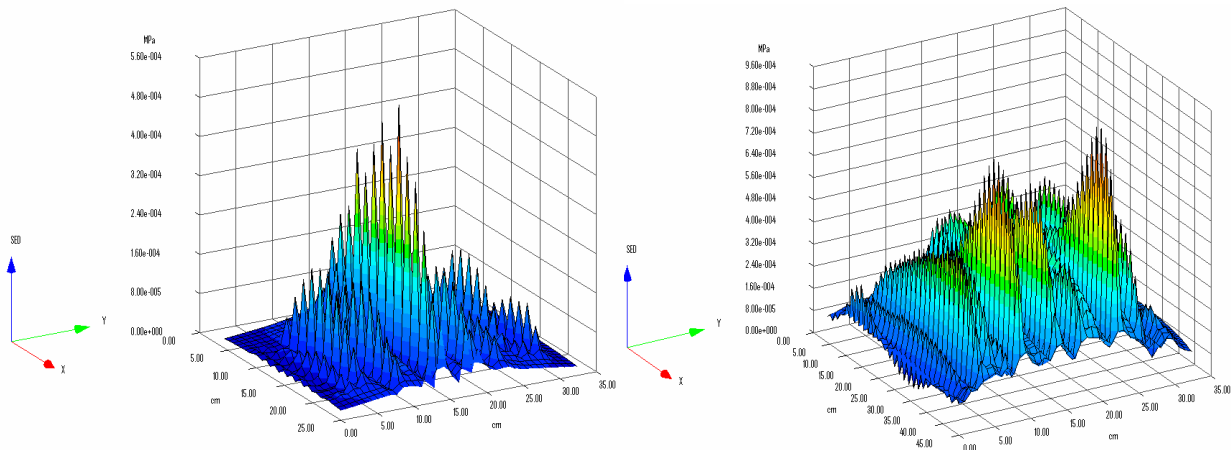


Figure 17. (a) SED on road pavement surface due to n- and (b) m-shaped single (wide base) tyre.

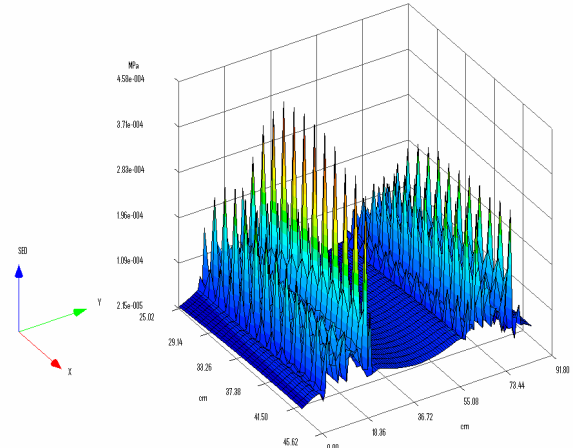
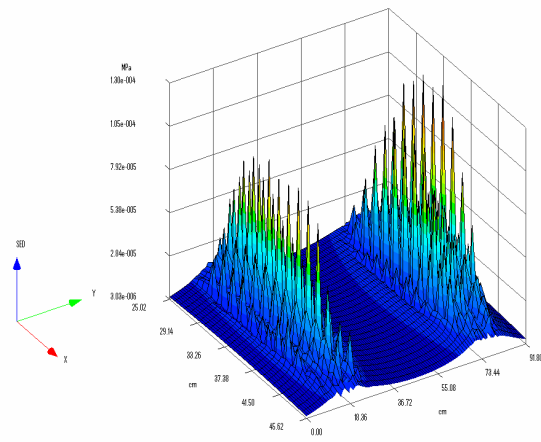


Figure 18. (a) SED on road pavement surface due to n- and

(b) m-shaped dual tyres.

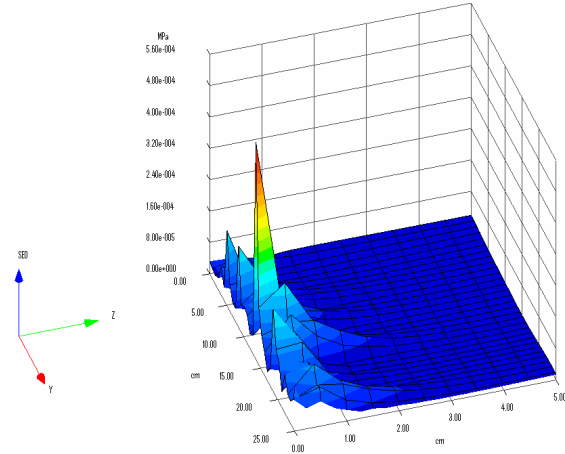
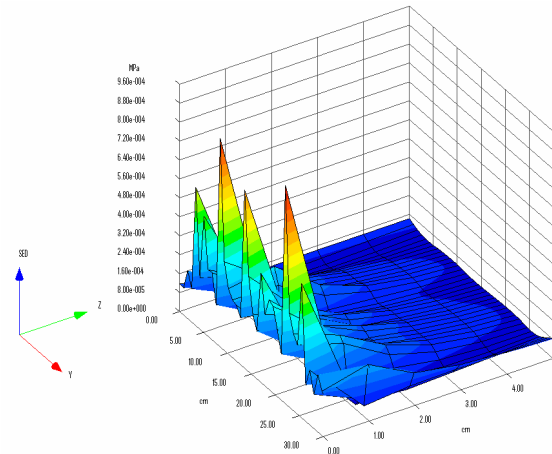


Figure 19. (a) Dissipation of SED with depth (m-shape) and

(b) n-shaped, single tyre.

Figure 17 (a) and **Figure 18 (a)** show results of SEDs on the surface of the road pavement under n-shaped contact stresses for single and dual tyres, respectively. The maximum SED value for single tyre is 5.53×10^{-4} MPa and 1.3×10^{-4} MPa for dual tyres. Moreover, **Figure 17 (b)** and **Figure 18 (b)** show results of SEDs on the surface of the road pavement under m-shaped contact stresses for single and dual tyres, respectively. The maximum SED value for single tyre is 9.29×10^{-4} MPa and 4.58×10^{-4} MPa for dual tyres. As an example, results shown in **Figure 19 (a)** and **(b)** indicate that the SED profile dissipates quite rapidly with depth for both the applied n and m-shapes of vertical stress in the given pavement example. Further, for

the type of 3D SIM measured contact stresses, the area with the highest potential for failure (cracking or permanent deformation, (i.e. “hot spots”) appears to be in the top 5 to 10 mm of the road surface. This is quite contrary to the conventional wisdom that the bottom of the top layer is prone to cracking (fatigue failure) and top of subgrade soil is prone to permanent deformation (rutting). These observations are strongly supported by recently observed rutting profiles at various HVS field test sites as shown in **Figures 7, 10 and 11**. However, more research is needed to confirm above finding with further field tests on different pavement types.

11. Concluding Remarks

Over the years, researchers and pavement engineers have not succeeded in explaining some of the failure mechanisms observed in our roads using conventional road analysis approach. However, results from this study have shown that SIM technology together with SED and numerical analysis technique may be used to identify areas within the road pavement sections with high potential for failure.

Consideration of 3D tyre-pavement contact stresses based on SED indicates that:

- Depending on the shape of the vertical contact stress distribution, the damaging effect in terms of SED of the single tyre appears to be 2.0 to 4.3 times higher than dual tyres under the same total loading.
- For both tyres, the damaging effect appears to be between 1.7 and 3.5 higher for the m-shape contact stress distribution.
- The top 5 mm to 10 mm of road pavements is potentially more prone to failure (top-down cracking or rutting) than was perhaps realised in the past.

12. Recommendations

Further research work is needed to establish if this trend is similar for all road pavement structures in South Africa before it is safe to argue against the use of single tyres or make recommendation on tyre inflation pressure for HVs.

13. References

BOSMAN, J. 2004, Traffic Loading Characteristics of South African Heavy vehicles 8th International Symposium on Heavy Vehicles, Weights and Dimensions. Loads, Roads and the Information Highway. Misty Hills Conference Centre, Muldersdrift, Gauteng, South Africa.

BOSMAN J. 2005, Heavy Vehicle Traffic Composition as Means of Classifying Roads. Proceedings of the 15th International Road Federation World Meeting Bangkok, Thailand. Paper 026.

BOUSSINESQ, J. 1885. Application des Potentiels a l'etude de l'equilibre et du Mouvement des Solids Elastiques. Gauthier-Villars, Paris.

BURMISTER, D. M. 1943. The General Theory of Stresses and Displacements in Layered Systems

and Applications to the Design of Airport Runways. *Proceedings, Highway Research Board*, Vol. 23, pp. 126-144.

CSIR 2007. The Fourth Annual State of Logistics Survey for South Africa, 2007. *Logistics for regional growth and development*. ISBN: 978-0-7988-5574-7. Downloadable from CSIR Web Site: <http://www.csir.co.za/sol/-Website> accessed 20 August 2008.

DE BEER, M, FISHER, C, AND JOOSTE, F J, 1997. Determination of pneumatic tyre/pavement interface contact stresses under moving loads and some effects on pavements with thin asphalt surfacing layers. 8th International Conference on Asphalt Pavements (ICAP '97). Proceedings of the conference held in Seattle, Washington, 10 -14 August 1997, USA.

DE BEER, M. AND SADZIK, E. 2007. Comparison of Contact Stresses of the Test Tyres used by the one third scale Model Mobile Load Simulator (MMLS3) and the full-scale Test Tyres of the Heavy Vehicle Simulator (HVS) - a summary. The Challenges of implementing Policy ?. SATC 2007: The 26th Annual Southern African Transport Conference and Exhibition, Pretoria, South Africa, July 9-12, 2007, pp 13. (ISBN 1-920-01702-X).

DE BEER, M, 2007. Stress-In-Motion (SIM) - A New Tool for Road Infrastructure Protection ?. WIM Session 7: International Conference on Heavy Vehicles (HVPari2008) – May 19-22, 2008, Paris/Marne-la-Vallée.

DE BEER, M, FISHER C and SADZIK E M 2008. Towards Quantifying Horizontal Stresses of Free-Rolling Pneumatic Rubber Tyres on Road Surfacing SATC 2008: The 27th Annual Southern African Transport Conference and Exhibition, Pretoria, South Africa, July 7-11, 2008, pp 16.

HUANG, Y. H. 2004. *Pavement Analysis and Design 2ND Edition*. Pearson Prentice Hall. Upper Saddle, NJ 07458

LE ROUX, M. (2007), Toll Roads N3TC. *Personal Communication with second author*.

LOVE, A. E. H. 1923. *Treatise on the Mathematical Theory of Elasticity*. University Press, Cambridge, England.

MAINA, J. W. and MATSUI, K. 2004. Developing software for elastic analysis of pavement structure responses to vertical and horizontal surface

loadings. *Transportation Research Record (TRB)*, 1896. pp. 107-118.

MCGHEE, K.H. 1999. Summary of the Proposed 2002 Pavement Design Guide, NCHRP Project 1-37A.

MORGAN, G, POULIKAKOS, L, ULISES, ARRAIGADA M, MUFF, R AND PARTL, M. 2007. Stress-in-Motion Measurements of Heavy Vehicles from the Swiss Footprint Monitoring Site. WIM Session 7: International Conference on Heavy Vehicles (HVPParis2008) – May 19-22, 2008, Paris/Marne-la-Vallée.

News24, 2008. <http://www.news24.com/> "Potholes hitting South Africa (26/02/2008)".

SAICE, 2006: The SAICE Infrastructure Report Card for South Africa: 2006.

THEYSE, H. L., MAINA, J. W., KANNEMEYER, L. 2007. Revision of the South African Flexible Pavement Design Method: Mechanistic-Empirical Component", 9th Conference on Asphalt

Pavements for Southern Africa, GICC, Gaborone, Botswana.

TIMOSHENKO, S. and GOODIER J. N. 1951. *Theory of Elasticity*. New York: McGraw-Hill Book Company, Inc.

PERDOMO, D., and NOKES, B. 1993. Theoretical Analysis of the effects of Wide-Base Tires on Flexible Pavements using CIRCLY. *Transportation Research Record (TRB)*, 1388. pp. 108-119.

14. Endnote

The authors wish to express gratitude to Gauteng Department of Public Transport Roads and Works (GDPTRW) as well as South African Bitumen Association (SABITA) who provided funding for part of the Heavy Vehicle Simulator (HVS) testing for this project. In addition, the acting Director of CSIR Built Environment is acknowledged for the permission to publish this paper.