Improved Performance Evaluation of Road Pavements by Using Measured Tyre Loading

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Abstract

This paper presents evaluation of road pavement response under the loading of typical dual and single truck tyre configurations. Locally developed Stress-In-Motion (SIM) technology was used to quantify three-dimensional (3D) shapes of the tyre-road pavement contact stresses. The measured stresses were used as input for multi-layer linear elastic analyses in order to demonstrate improved evaluation of pavement performance, especially on the surface of the road structure. Strain Energies of Distortion (SEDs) at various sections within the road pavement structure were determined. It is shown that the concept of SED as a response parameter that quantifies "*potential for failure*" of a road pavement structure seems to resonate well with the applied tyre stresses and their different shapes. It was also found that single wide-base tyres introduce more than double the *potential for failure* compared with the dual tyre configuration on the same pavement. Furthermore, this study demonstrates that under-inflated, heavily-loaded tyres may cause more damage on the surface of the road compared to correctly inflated tyres. The combination of SIM technology and SED from numerical modelling may be used to identify areas of high potential for failure on the road surface.

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. Increased economic activities, in recent years, have resulted in considerable growth in both passenger and freight traffic volumes. A study conducted four years ago found a Total Vehicle (Combination) Mass (TVM/TCM) from approximately 253 000 registered heavy vehicles (HVs), out of which 26 000 were buses, to have exceeded 3.5 tonnes (Bosman, 2004). Additionally, the Fourth annual State of Logistics Survey for SA 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**.

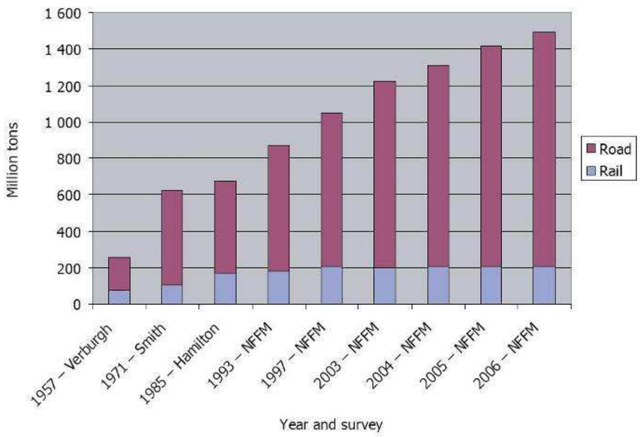

Figure 1. Historical freight transport data (CSIR, 2007).

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 the impact of the increased loading on roads, studies on tyre-road interaction 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 improved performance. This paper informs on and compares 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 (SED). The concept of SED is used as a pavement response parameter that may help to compare different pavement structures in terms of their *potentials for failure*.

2. Quality and importance of road infrastructure in SA

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). *Note* The terms “road” and “pavement” are used interchangeably in this article, *excluding* “sidewalks”. 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 SA road pavement 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, the N3 has already carried the equivalent 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

Recently, there has been a move towards classifying SA 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 has been 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, two main types of truck tyres are widely used on our roads – the single (or so-called wide-base tyre) and the conventional dual truck tyres. 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 smaller than two "footprints" from 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 improvement of overall road 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 structural 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, a new locally developed technique whereby individual multi-dimensional (3D) tyre-road contact forces (and hence actual contact stresses) are measured, is first 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 from SIM could potentially be used by consultants, road authorities and road managers to enhance optimization of design, construction, maintenance of existing and new roads, and their long-term performance.

As a demonstration of SIM technology, tyre-road contact stress measurements were carried out, in 2003, on a busy national road (N3) in SA from the port of Durban to the inland province of Gauteng (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. SIM measurement series were 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. It was found that the SIM system compared favourably with WIM scales covering TVM/TCM of 2 292 HVs; individual tyre mass weights (45 165 tyres) and typical tyre inflation pressures on HVs (1070 tyres) (De Beer, 2007). Suggestions for enhanced mechanistic-empirical pavement design, based on the concept of 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 2** 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 3**, 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 and with a real truck on the N3 in 2003, respectively. 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 of 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 variation 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 measured simultaneously with the SIM system but are not presented here (see De Beer et al, 1997, 2007, 2008). The foregoing is officially referred to as tyre “*finger printing*” which enables 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 (GDPTRW) and the SA 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**.

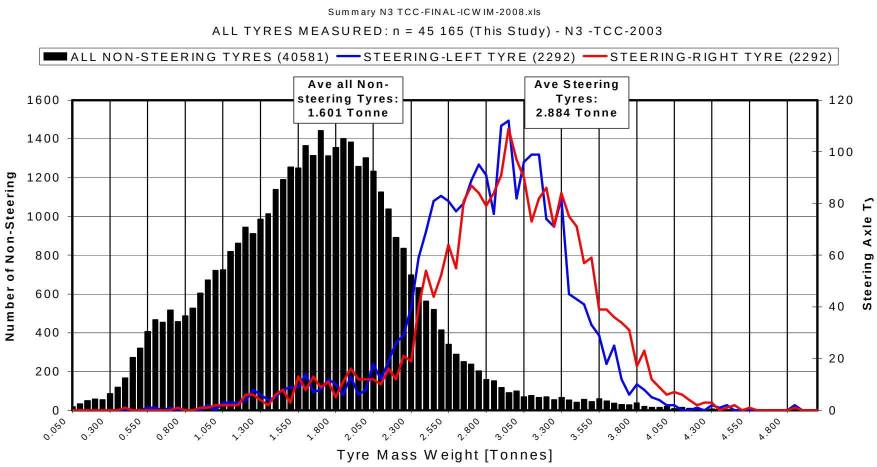

Figure 2. Typical distributions (from SIM) in tyre Mass Weights in 2003 on the N3 North bound, showing also a difference of approximately 1.2 tonne heavier loading on the steering tyres.

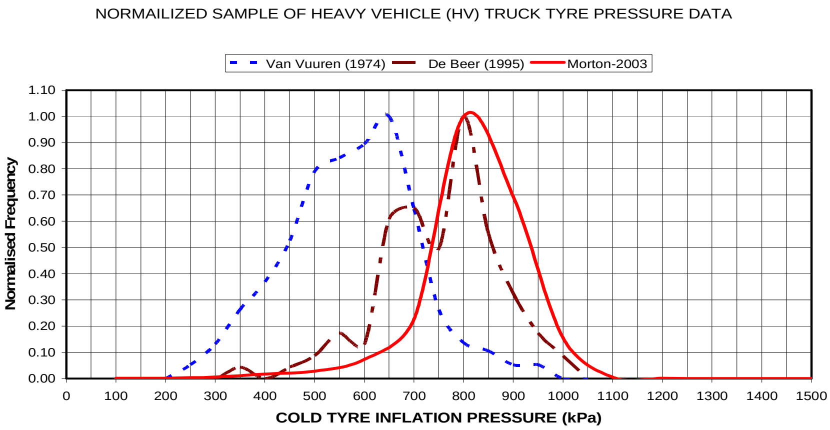

Figure 3. Some historical tyre Inflation pressure data of Heavy Vehicles since 1974. Note the increase in inflation pressure of truck tyres since 1974, which is almost 20 per cent over 20 years.

Figure 4. Dual Pad SIM system under HVS tyre testing.

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

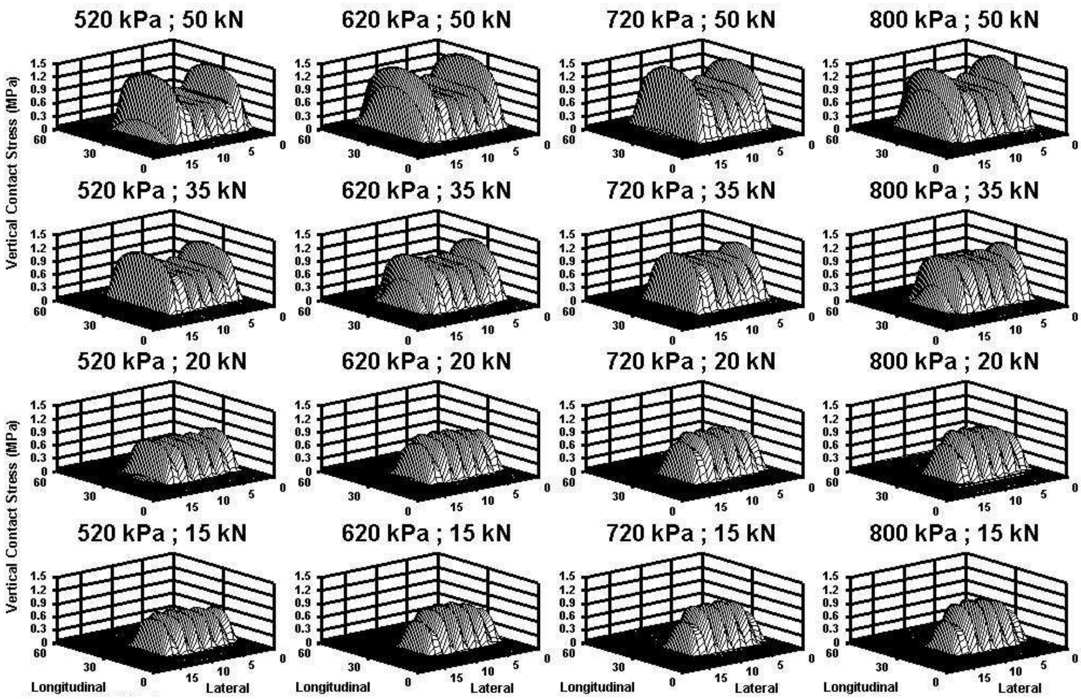

Figure 6. Vertical tyre pavement contact stress profiles of a single 11R22.5 tyre (HVS) over a range of tyre loading (15 kN to 50 kN) on Y-axis and inflation pressures (520 kPa to 800 kPa) on X-axis.

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 ºC.

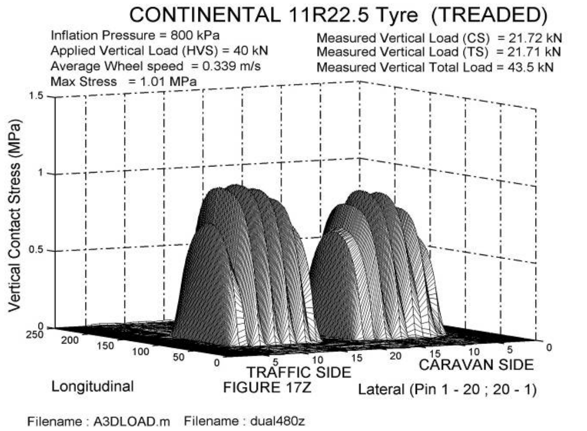

Figure 8. Typical vertical contact stress (Z) distribution (n-shape) of the 11R22.5 dual HVS tyres at a loading of 40 kN and 800 kPa Inflation pressure

Figure 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 ºC (n-shape- Dual tyre loading – see Figure 8)

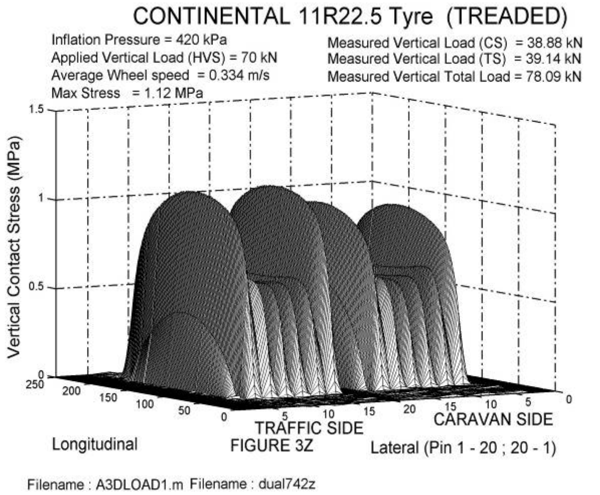

Figure 9. Typical vertical contact stress (Z) distribution (m-shape) of the 11R22.5 dual HVS tyres at a loading of 60 kN and 420 kPa Inflation pressure

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 ºC (m-shape- Dual tyre loading – see Figure 9)

7. Equations for mechanistic road analysis

The key to proper design of road pavements and improved performance is in 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 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 numbers 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 in **Figure 3** (X, Y, Z) is a global coordinate system, while local coordinate system is represented by x, y, z. 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:

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

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:

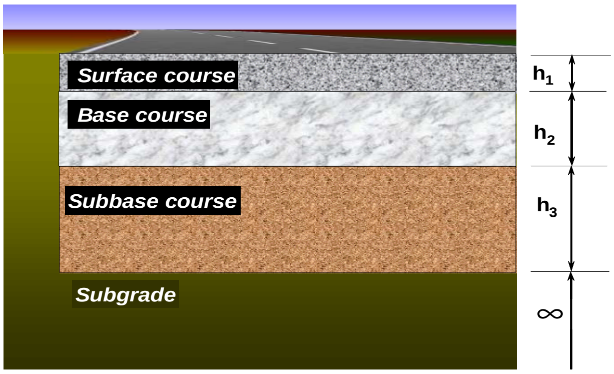

Figure 12. Typical multi-layered road pavement structure

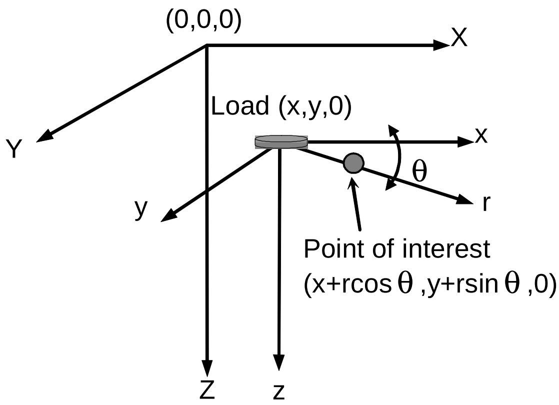

Figure 13. Global and local coordinates of tyre-road system

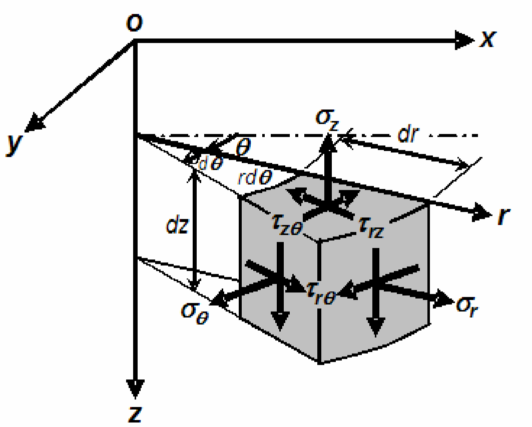

Figure 14. Infinitesimal element at equilibrium

$$\nabla^4\Phi = 0 \qquad\qquad (2)$$
$$\nabla^2\Psi = 0$$

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

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

Making use of strain-displacement and stress-strain relationships from Hooke's law, stresses may be expressed in terms of displacement functions as show in equation (4):

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

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 and ν is Poisson's ratio of the material.

Solutions for the displacement functions Φ and Ψ may be determined by using Hankel transform. After that, responses in terms of road pavement displacements, stresses and strains may 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 the 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 (x, y, z) as well as cylindrical (r,θ,z) coordinate systems with their origins at the centre of the respective load. For each load, structural analysis is then carried out based cylindrical axes and results at a particular analysis point of interest are converted to common global coordinate system. Because the assumptions listed in Section 7 hold, the principle of superposition may then be utilized. Therefore, results at each analysis point from multiple loads, which are now represented in global Cartesian coordinate, may be summed up in order to obtain the final results.

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

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

where

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

It is assumed that the x-axis of local Cartesian coordinates is in the same direction as the X-axis of the global Cartesian coordinates. A 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 may 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 limiting 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:

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

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

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

It is assumed in this paper that with this approach, points within the pavement structure that have higher values of 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 systems 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

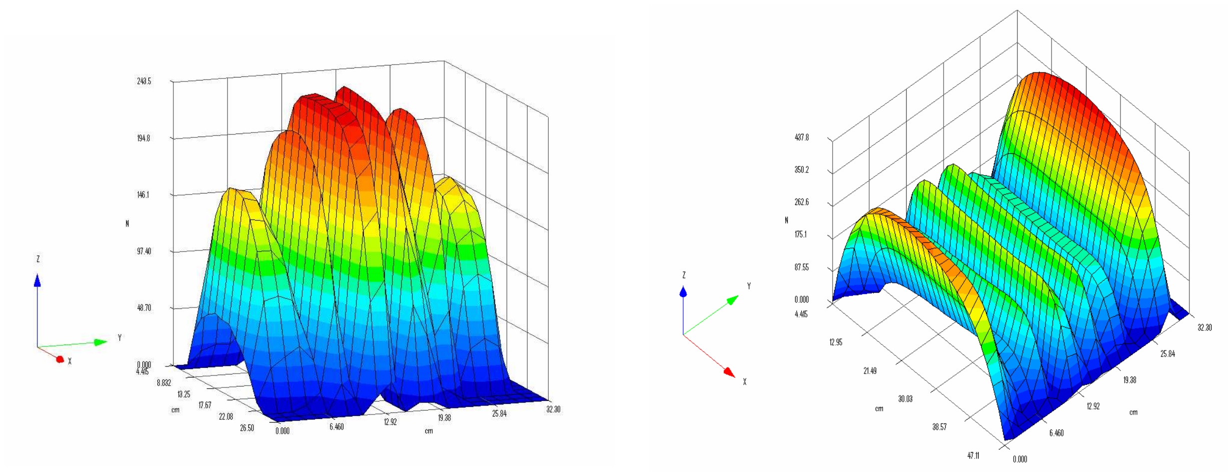

Figure 15. (a) Single tyre - n-shaped vertical contact stress and (b) m- shaped vertical contact stress

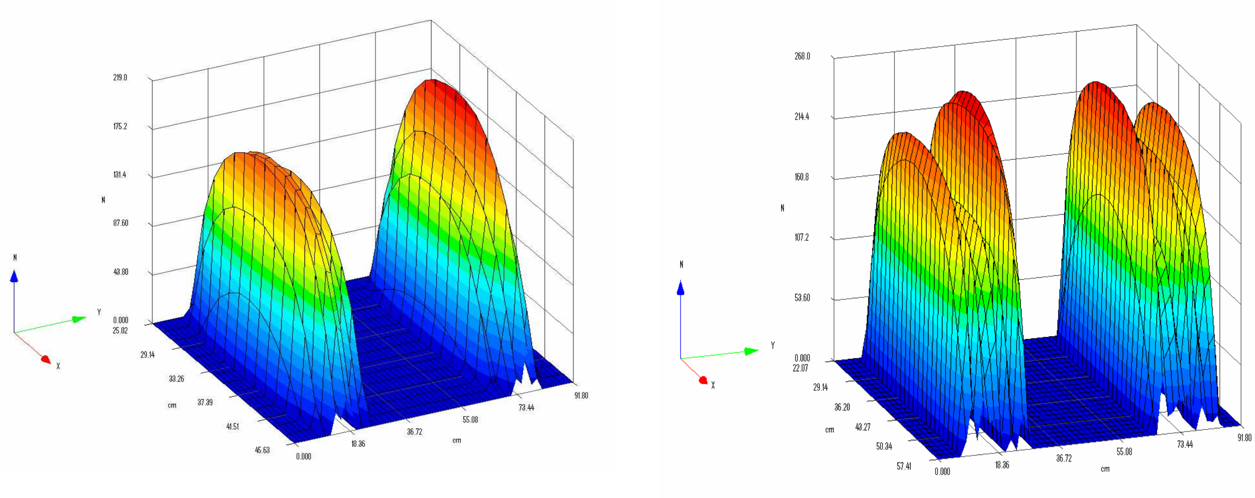

Figure 16. (a) Dual tyre - n- shaped vertical contact stress and (b) m- shaped vertical contact stress

Numerous computer analysis runs were carried out for the same pavement structure shown in Table 1 in order to identify differences in pavement responses, if any, 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 a significantly high number of loads (3-dimensional measured SIM data) and road pavement analysis points were 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).

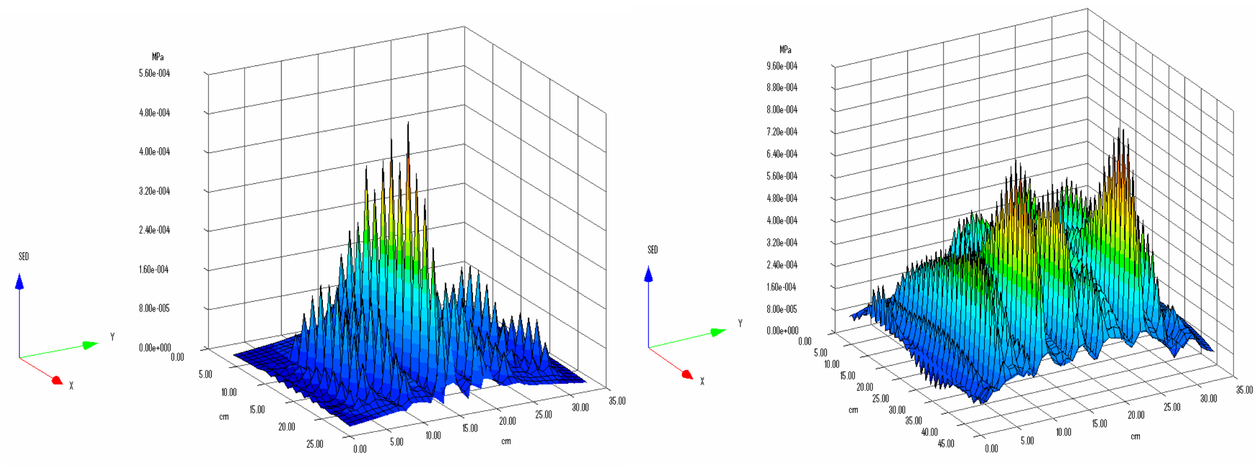

Figure 17. (a) SED on road pavement surface due to n- and (b) m-shaped single (wide base) tyre

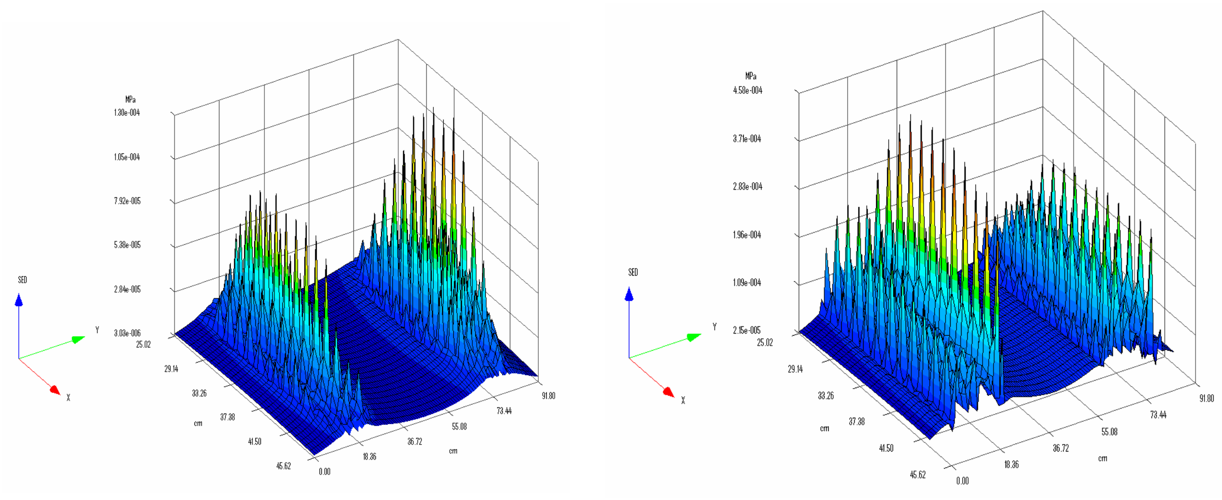

Figure 18. (a) SED on road pavement surface due to n- and (b) m-shaped dual tyres

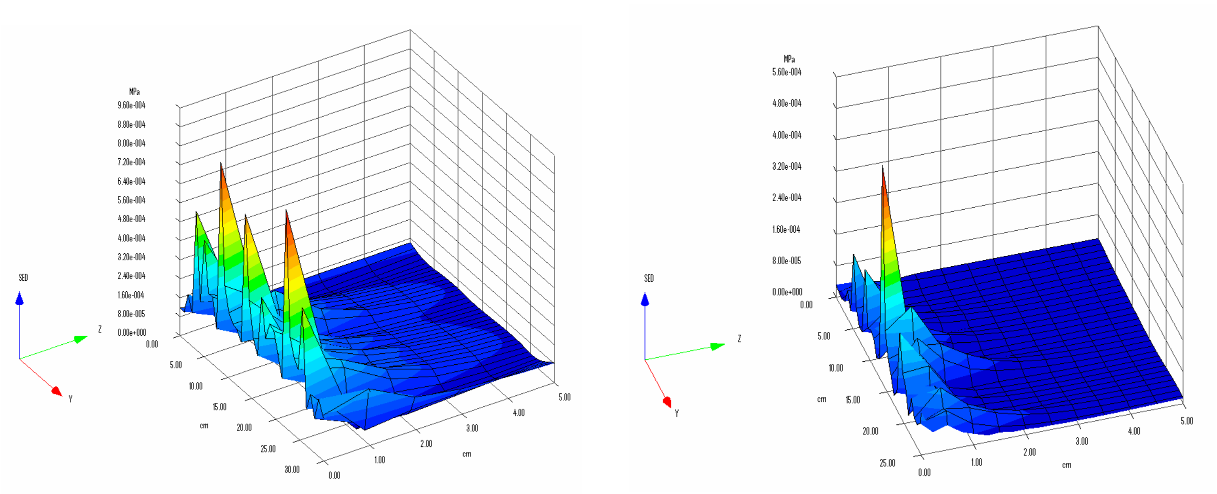

Figure 19. (a) Dissipation of SED with depth (m-shape) and (b) n-shaped, single tyre

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 a single tyre is 5.53x10^{-4} MPa and 1.3x10^{-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 9.29x10^{-4} MPa and 4.58x10^{-4} MPa for dual tyres. 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 layer. This is quite contrary to the conventional wisdom that the bottom of the top layer is prone to cracking (fatigue failure) and the 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 the above finding with further field tests on different pavement types.

11. Summary of research findings

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. Conclusions

Findings from this research study are applicable to the one type of pavement structure that was evaluated. The concept of SED as a response parameter that quantifies road pavement's "*potential for failure*" seems to resonate well with the applied tyre stresses and their different shapes. It was also found that single wide-base tyres induce more than double the *potential for failure* compared with the dual tyre configuration on the same pavement. Further, this study demonstrated that under-inflated, heavily-loaded tyres may cause more damage on the surface of the road compared to correctly inflated tyres. The combination of SIM technology and SED from numerical modelling may be used to identify areas of high potential for failure on the road pavement system.

13. 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 a recommendation on tyre inflation pressure for HVs.

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15. Endnote

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