MODELLING VERTICAL UNIFORM CONTACT STRESS OF HEAVY VEHICLE TYRES

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ABSTRACT

The field of tyre dynamics is a relatively new, but highly complex field of engineering. The testing and modelling of various tyres in order to determine stress distributions of tyres on the road surface, under varying conditions, remains a relevant and important field of study. The information from these studies are essential to understanding vehicle dynamics as the small contact patches between the vehicle tyres and road surface is the only area of interaction between the entire vehicle and the road surface. The contact stress data is also essential in the calculation of road wear characteristics of tyres and vehicles. Different models exist to estimate the contact stress between the tyre and road surface, but most contain assumptions that limit their applicability to a small set of tyres under very specific load cases. This paper considers the development of mathematical models that are used to estimate the vertical uniform contact stress for three types of heavy vehicle tyres. The three tyres studied are 315/80 R22.5, 385/65 R22.5 and 425/65 R22.5 tyres. The models have been developed through the use of tyre testing data obtained from the Stress-In-Motion (SIM) system. It was found that 4th order polynomials provided the most accurate stress results over the selected operating range of 25 kN to 45 kN which is the typical load range for heavy vehicle tyres due to legal axle load limits. The polynomial formulas require only the tyre inflation pressure and vertical tyre load as inputs, in order to estimate the vertical uniform contact stress. The models developed correlate well with the test data and showing an average absolute error of less than 2 %.

1 INTRODUCTION

1.1 Background

The relatively small contact area between the tyres of a heavy vehicle and the road surface is the only interaction between the vehicle of several tonnes and the road surface. This contact area is traditionally referred to as the “footprint” (Hjort, Haraldsson, & Jansen, 2008). The performance-based standards (PBS) or “Smart Truck” pilot project has been operational in South Africa since 2007 and currently has approximately 162 vehicles spread over various industries participating in the project (CSIR monitoring data). In order for a vehicle to be considered for the pilot project, the vehicle must pass a vehicle dynamics safety assessment as well as a benchmarked road wear assessment performed using mePADS (CSIR, Mechanistic Emperical Pavement Design and Analysis Software, 2008). Understanding the contact stresses at the tyre/road interface is an important field of study as it directly influences the road wear results obtained from a road wear assessment.

The tyre-road pavement contact stresses are complex and dependant on numerous variables relating to both the tyres and the operating conditions. Factors include tyre inflation pressure (TiP), tyre width, wheel alignment, tread pattern, chemical composition of the rubber, tyre construction and tyre load (Yap, 1989). These factors have been a key area of research at the CSIR since the 1990's (De Beer, Sallie, & Van Rensburg, 2009).

Due to the competitive nature of the premium tyre industry, availability of information on the tyre-road pavement contact stress distributions is limited. Performing the necessary experimental work is also time-consuming and expensive and as such data in this regard is limited. Traditional analytical methods have assumed that the tyre contact stress area is round, with uniform contact pressure. Two methods are popular for determining either the circular contact area or the assumed uniform stress. Either one of these are required for a road wear assessment. The first is that the uniform stress at the tyre/road interface is equal to the tyre inflation pressure. The recommended tyre inflation pressure for a particular load is obtained from the European Tyre and Rim Technical Organisation (ETRTO) standards. Alternatively the contact area can be obtained assuming that the diameter of the contact area is equal to the width of the tyre (Roux & De Beer, 2011).

It is however known from experimentation that the tyre contact stresses are neither uniform nor circular in shape. Furthermore, the measured vertical contact stresses exceed the tyre inflation pressures by approximately 30 %. Overloaded and underinflated tyres may also result in contact stresses that exceed the tyre inflation pressure by two to three times (CSIR, 1997).The Stress-In-Motion (SIM) system has been used in South Africa since the 1990s to research the interaction forces between slow moving tyres and textured road surfaces (De Beer & Sallie, 2012). The SIM system is a unique measuring system that is used for the quantification of tri-axial (3D) tyre force/stress distributions (De Beer & Fisher, 2013). The uniqueness of the system is defined by a textured measuring surface in order to represent a typical "textured" road surface. A SIM measuring pad testing area consists of 1020 supporting pins and a transverse array of 21 sensing elements, covering the entire tyre contact patch. Each one of the sensing elements has a 9.7 mm diameter circular contact surface area (approximately 73.9 mm^2) and is dimensionally optimised, allowing measurements in various tyre rolling conditions on a textured measuring surface. The textured surface emulates a tyre-road contact surface and thus induces some pre-conditioning of tyre–road contact properties due to small gaps around all supporting and measuring pins. The system is installed flush with the road surface, on a rigid support base, and can be used for real tyre (or truck) rolling conditions. A single SIM measuring pad contains 63 strain measuring channels (3 × 21) for the sensing elements in order to capture forces/stresses in three dimensions. (De Beer & Fisher, 2013). An example of this SIM measuring pad is shown in Figure 1.1.

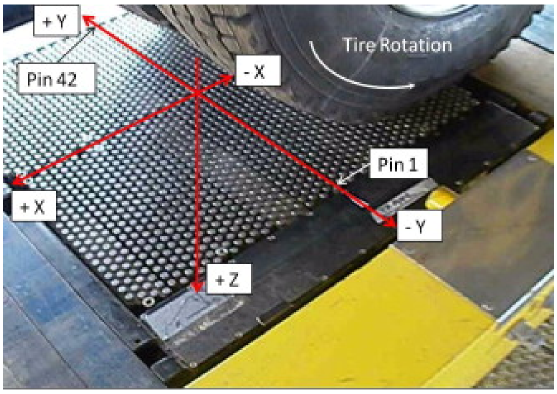


Figure 1.1: Stress-In-Motion (SIM) measuring pad (De Beer & Fisher, 2013)

Currently the results from SIM analyses of 33 tyres have been logged in the “TyreStress-Internal” application (CSIR, TyreStress-Internal software, 2014). These 33 tyres span over a wide range of tyres, from 275s to 445s and these include entries for both bias and radial tyres.

Research performed at the CSIR has suggested that the actual uniform contact stress values measured for tyres typically fall somewhere between the two traditional assumptions of uniform contact stress as described earlier (Roux & De Beer, 2011). This phenomenon is illustrated in Table 1.1.

Table 1.1: Uniform contact stress based on two assumptions compared with mean contact stress based on SIM measurements (Roux & De Beer, 2011)

Tyre Designation	Wheel Load (kg)	TiP (kPa)	Uniform Contact Stress (kPa)		
			Assumption 1	Assumption 2	Mean Measured
315/80R22.5	2500	590	590	315	514
315/80R22.5	3000	740	740	380	469
315/80R22.5	4000	850	850	505	657
425/65R22.5	4000	600	600	280	428
425/65R22.5	4500	700	700	315	514
425/65R22.5	5000	795	795	350	547
11R22.5	2000	580	580	320	368
11R22.5	2500	760	760	400	361

From the PBS analyses performed at the CSIR it has been noted that the majority of vehicles being studied are using the tyre type 315/80 R22.5 and a number of wide base tyres, specifically 385/65 R22.5 and 425/65 R22.5 tyres. These tyre types will subsequently be referred to as “315s”, “385s” and “425s”.

From the SIM database it was also discovered that the majority of tyres studied had the same type of tread pattern, namely the “Highway Rib” variation as shown in Figure 1.2. As a result only this tread pattern was considered during this paper.

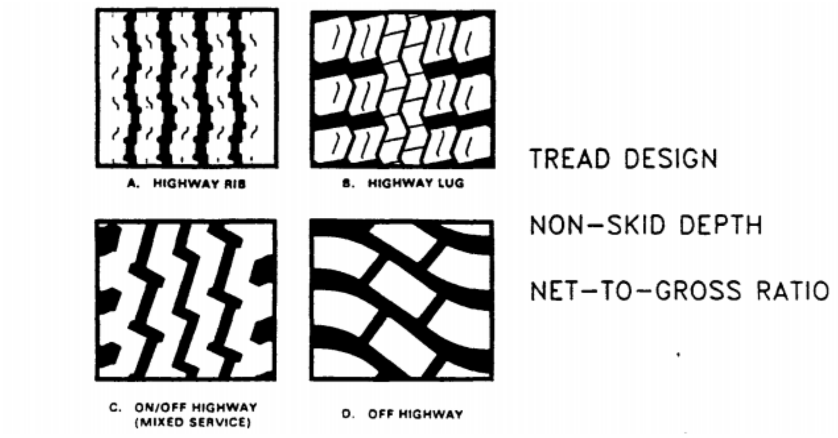
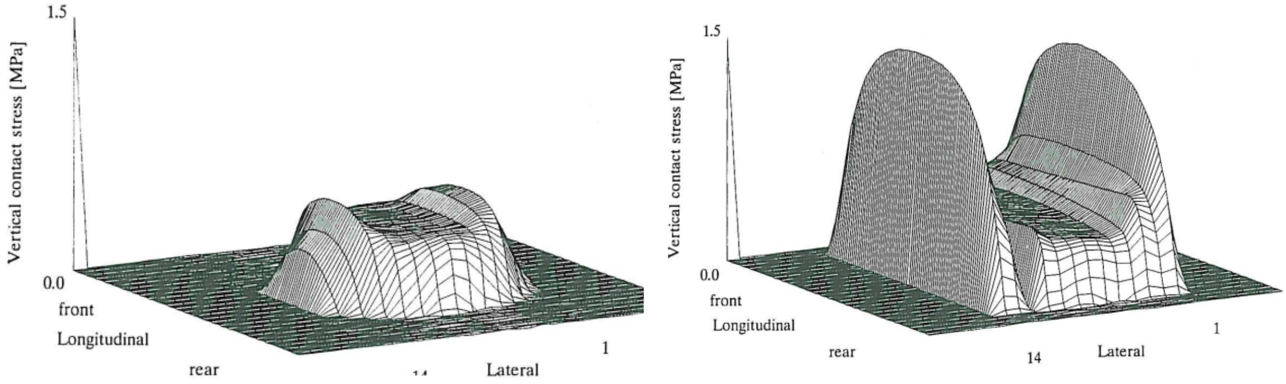


Figure 1.2: Different typical tyre tread patterns used on heavy

Currently no single equation exists in order to predict the actual measured uniform contact stress at the tyre/road interface for various tyre types.

A phenomenon worth mentioning is that generally the contact pattern (“fingerprint”) of a tyre changes from the well-known “n”-shape to the “m”-shape with increased tyre loading and/or reduced tyre pressure. This “n” and “m”-shape patterns refer to the shape of the curve of the peak stresses over the contact area (De Beer, 1994). Examples of an “n” and “m”-shape distributions are shown in Figure 1.3.



(a) (b)

Figure 1.3: (a)”n”-shape vertical stress distribution for a heavy vehicle tyre and (b) “m”-shape vertical stress distribution (De Beer, 1994)

1.2 Aim

This paper aims to develop a tyre/road interface stress model in order to estimate the uniform contact stress for three specific tyre types (315s, 385s and 425s).

1.3 Scope

Three tyres from the Stress-In-Motion (SIM) database have been used in the development of the functions used to estimate the uniform contact stress at the tyre/road interface. Multi-variate linear regression was used to develop the functions for the tyre contact stress. Furthermore only the “highway rib” tyre tread type/pattern was considered during this analysis and all other factors that may influence contact stress have not been considered.

2 METHOD

The “TyreStress-Internal” application developed by the CSIR was used to access the SIM test data. The entries for 315s, 385s and 425s were investigated to determine which had the most consistent data, with the least noise and fewest outliers.

The various methods used in the “TyreStress-Internal” application to estimate the tyre/road footprint area or the average contact stress were investigated in order to identify the most suitable method, i.e. the method that provides the most accurate estimation of the contact area or average uniform contact stress. This comparison between methods was done via visual inspection as well as from recommendations obtained from experts involved in the development of the “TyreStress-Internal” application.

After selecting the appropriate model, a test matrix was used to extract the necessary information from the data base. The test matrix consisted of obtaining the average measured uniform contact stress for a specific tyre relating to a specific tyre inflation pressure (TiP) and the wheel load. The data was extracted over the entire test range of tyre inflation pressures and available tyre loads.

After a sufficient amount of data points were obtained, various regression models were investigated to find one that best fitted the data. The models that produced the lowest average error over the sample range were then selected.

3 RESULTS AND DISCUSSION

Only one entry was available for 385s and it was not suited for the study as it had an off-road tread pattern, resulting in significant deviation in contact stress distribution. The highway rib tread pattern for the 425 tyre studied is shown in Figure 3.1.

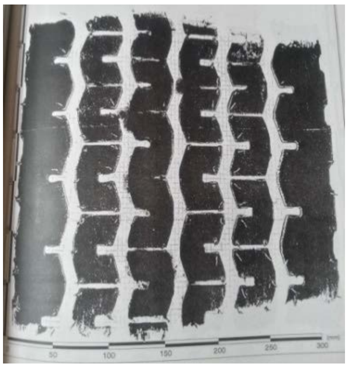


Figure 3.1: Tread pattern of the 425 tyre used during this study (De Beer & Fisher, 1997)

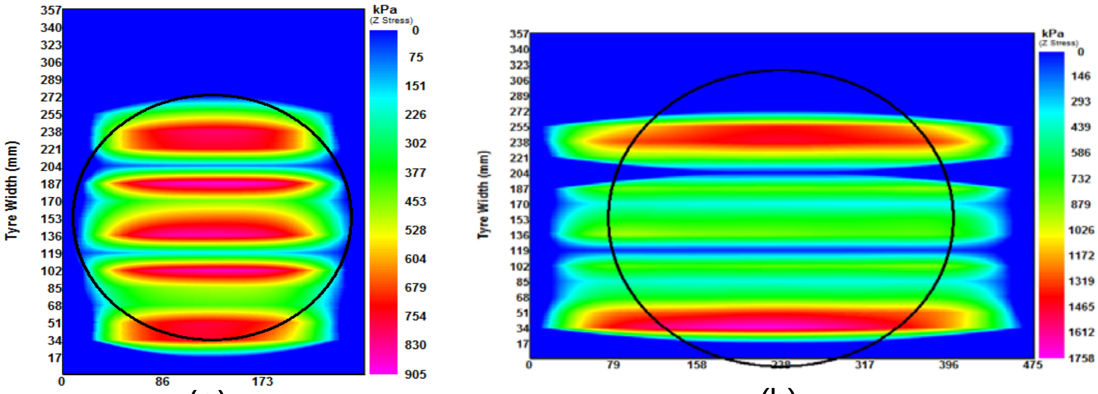
Of all the entries in the TyreStress application, one set of tyre data was selected for a 315 and one for a 425 tyre type. The selected tyres were:

1. NL04 - Tyre 6- 425-65 R22.5 R164BZ (New) (TuDelft-NL) 1996
2. SA04 - Tyre 8- 315-80 R22.5 (SA) 1996

The model selected to determine the tyre/road footprint (or uniform contact stress) was the so called “Equivalent Staggered Diamond”, available in the “TyreStress-Internal” data base This model uses the total number of pins that are in contact with the tyre during testing as well as an interpolation function to estimate the total contact area. This area is then converted into an equivalent circle in order to be used in the mePADS software. An example of the area as calculated by the model is shown Figure 3.2a for the case of a low vertical tyre load and in Figure 3.2b for the case of a high vertical tyre load. It can be seen that this “Equivalent Staggered Diamond” model provides an accurate estimation of the contact area between the tyre and test surface, as represented by the black circle. It is also noted that at relatively low loads the contact area is approximately circular. At higher loads however the contact area is more rectangular. The stress distribution is however never uniform as is generally assumed.

The data obtained by performing a grid search using the “TyreStress-Internal” application for 315s and 425s respectively are shown in Table 3.1 and Table 3.2.

The results illustrating the relationship between the tyre load and the uniform contact stress were plotted in order to visualise the data to look for structure contained therein. Figure 3.3 illustrates the relationship between the axle load and the uniform contact stress at various tyre inflation pressures for Tyre 8 (315).



(a) (b)

Figure 3.2:(a) Illustration of contact area for a low load case as calculated using "Equivalent Staggered Diamond" model for Tyre 8 at a tyre load of 23 kN and TiP of 500 kPa (b) Illustration of contact area for a high load case as calculated using "Equivalent Staggered Diamond" model for Tyre 8 at a tyre load of 75 kN and TiP of 500 kPa.

Table 3.1: Average uniform contact stress for Tyre 8 (315) as calculated by the "Equivalent Staggered Diamond" model

Load (kN)	Tyre Inflation Pressure (kPa)					
	500	**600**	**700**	**800**	**900**	**1000**
25	556	652	618	686	686	716
30	592	658	667	716	729	766
35	633	694	719	760	778	820
40	672	734	770	808	827	875
45	720	778	815	853	875	922
50	789	840	858	898	920	964
55	811	856	895	937	961	1006
60	833	882	929	974	1001	1046
65	856	911	963	1011	1040	1086
70	878	940	996	1048	1079	1125
75	901	970	1029	1083	1117	1164
79.6	921	991	1056	1114	1153	1199

Table 3.2: Average uniform contact stress for Tyre 6 (425) as calculated by the "Equivalent Staggered Diamond" model

Load (kN)	Tyre Inflation Pressure (kPa)					
	500	**600**	**700**	**800**	**900**	**1000**
26	500	531	571	596	631	619
30	518	553	600	627	662	659
35	545	585	638	669	705	709
40	573	618	677	711	751	760
45	602	651	716	754	797	810
50	631	684	755	795	841	858
55	654	706	764	812	867	870
60	677	725	778	829	887	891
65	705	746	795	849	910	915
70	737	769	814	869	934	940

It is clear that the uniform contact stress increases as the tyre load increases for all tyre inflation pressures due to the fact that the load increases proportionally more than the contact area. Secondly, it is evident that the uniform contact stress increases at a specific tyre load as the tyre inflation pressure increases. This is due to the fact that higher inflation tyre pressures cause the contact patch surface area to reduce as result of less tyre deformation. It was also observed that the uniform tyre stresses for the 425 tyres were relatively lower than that for the 315 tyres at the same tyre load and tyre inflation pressure. The general shape of the 425 tyre graph is however, similar. All of these trends are in line with what is expected from the theory.

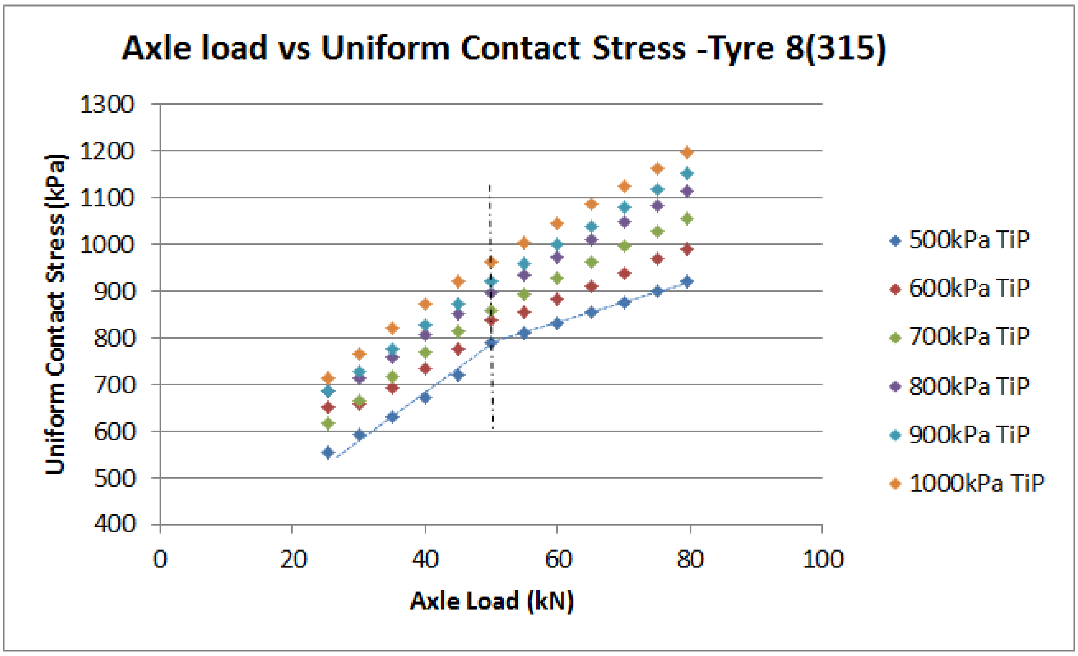
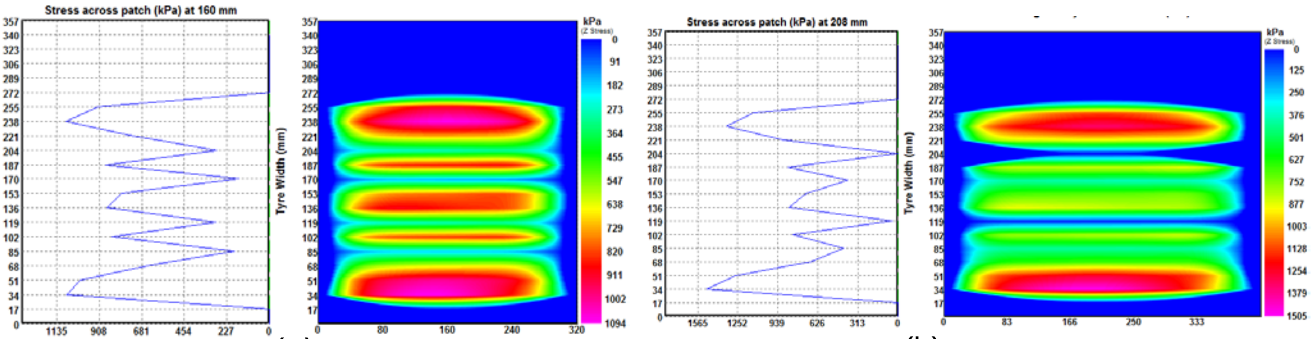


Figure 3.3: Tyre load vs uniform contact stress for Tyre 8 (315) at various tyre inflation pressures (TiP)

One unexpected trend is the change in gradient in the curves as can be seen at a tyre load of 50 kN. On either side of this change on gradient the curves follow an approximate straight line. The slope of these curves are however different on either side. It is postulated that this change in gradient is the transition from the “n”-shape” to the “m”-shape when considering the tyre contact stress profile across the tyre contact patch. This hypothesis seems to be supported based on the results shown in Figure 3.4. A similar trend was observed for Tyre 6, but at a different tyre load.



(a) (b)

Figure 3.4 : (a) Illustration of the contact area stress distribution for tyre 8 at a load of 40 kN and TiP of 500 kPa which has an approximate “n”-shape distribution (b) Illustration of the contact area stress distribution for tyre 8 at a load of 60 kN and TiP of 500 kPa which has an approximate “m”-shape distribution

A regression model fitted to the entire data range was found to have a significantly lower correlation when compared to individual curves fitted to the two distinct regions around this observed change in gradient. As a result it was decided to only develop equations for the normal operating range for these tyres which is approximately in the 25 kN to 45 kN load range per tyre. This tyre operating range is based on current legal axle loads imposed on heavy vehicles in South Africa. This range falls to the left of the observed change in gradient in the data set where good correlation was found.

In order to develop a model that could also be used to estimate the uniform stress for 385 tyres, linear interpolation (based on the tyre width) was performed between the known 315 and 425 tyre data.

The data points for all of the tyres in the normal load range of truck tyres were used for the regression model. The first approach was to develop a single/universal model to be used for any tyre width within the range of available data, using tyre width, vertical tyre load and inflation pressure as the input variables.

The second approach was to develop individual models for uniform contact stress of each tyre studied, using tyre inflation pressure and vertical tyre loads as input variables.

It was found the multivariate linear regression with a 4th order polynomial as a basis function gave the lowest average errors for both approaches.

In the case of the universal model it was found that a relatively accurate model could be developed with an average error of 3.25 %, however the maximum errors were found to be in excess of 10 %. It was noted that the region of the maximum errors was specifically where the tyre inflation pressure closely matches the recommended tyre inflation pressure as per the ETRTO standards (Roux & De Beer, 2011)

The results for the individual models showed an even greater accuracy, with a maximum average error of 1.64 %, in the case of the 425 tyre. There are a total of 15 terms in each of the equations, with the general form given in Equation 4.1.

$$\begin{gathered}\sigma_{Uniform\,Contact\,Stress} = a_1 + a_2\sigma_{TiP} + a_3(\sigma_{TiP})^2 + a_4(\sigma_{TiP})^3 + a_5F_{tyre} + \\ a_6\sigma_{TiP}F_{tyre} + a_7(\sigma_{TiP})^2F_{tyre} + a_8(\sigma_{TiP})^3F_{tyre} + a_9\left(F_{tyre}\right)^2 + a_{10}\sigma_{TiP}\left(F_{tyre}\right)^2 \\ + \\ a_{11}(\sigma_{TiP})^2\left(F_{tyre}\right)^2 + a_{12}\left(F_{tyre}\right)^3 + a_{13}\sigma_{TiP}(F_{tyre})^3 + a_{14}(F_{tyre})^4 + a_{15}(\sigma_{TiP})^4\end{gathered} \tag{4.1}$$

Where:

- $\sigma_{Uniform\,Contact\,Stress}$ is the calculated uniform contact stress at the tyre/road contact area [kPa]
- a_x are the constants
- σ_{TiP} is the tyre inflation pressure [kPa]
- F_{tyre} is the vertical tyre load [kN]

The errors associated with the different equations are listed in Table 3.3, whilst the constants used in the general Equation 4.1 are listed in Table 3.4.

Table 3.3: Errors associated with different equations for three tyre types

Error	315s	385s	425s
Maximum error	614 %	4.12 %	6.02 %
Average absolute error	1.19 %	1.04 %	1.64 %

Table 3.4: Constants used in the contact stress equations for the different tyres

Constant	Weights for 315s	Weights for 385s	Weights for 425s
a_1	2.46E-03	5.91E-04	5.96E-03
a_2	2.18E-03	8.23E-03	-5.42E-03
a_3	5.08E-03	5.10E-03	3.78E-03
a_4	-6.18E-06	-4.26E-06	-3.46E-06
a_5	1.12E-03	-3.57E-03	-4.46E-04
a_6	-3.40E-05	-2.01E-02	4.16E-03
a_7	-1.02E-04	-1.62E-04	-1.24E-04
a_8	6.56E-08	3.58E-08	-7.84E-09
a_9	-4.13E-03	-1.48E-03	-2.17E-03
a_{10}	1.42E-03	2.82E-03	1.96E-03
a_{11}	-2.85E-07	1.44E-06	2.37E-06
a_{12}	2.10E-03	-1.52E-03	-4.66E-03
a_{13}	-7.15E-06	-3.94E-05	-4.88E-05
a_{14}	-7.07E-05	5.50E-05	1.99E-04
a_{15}	2.12E-09	1.45E-09	1.57E-09

4 CONCLUSION

Uniform tyre/road interface stress models have been developed for 315, 385 and 425 tyres that accurately predict the average vertical uniform contact stress between the road and tyre surface. These equations were developed for the normal operating range of truck tyres, i.e. between 25 kN and 45 kN.

A single/universal equation that could be applied to all tyre types studied was developed, but it was found that the errors at critical operational points as recommended by the ERTRO standards were large. As a result, individual equations were developed for each of the three tyres in the study. The errors associated with these equations are relatively low, with the average absolute errors being less than 2 %. The input parameters for these functions are the tyre inflation pressure and vertical tyre load.

The models developed will be incorporated in to road wear assessments as performed by the CSIR in order to obtain more accurate results. The value and need for road wear analyses are increasing as the importance and cost to develop and maintain the road infrastructure is understood. Further work in this field is therefore needed.

5 ACKNOWLEDGEMENTS

The authors would like to sincerely thank the reviewers for their valuable inputs.

6 RECOMMENDATIONS

In order to improve the confidence in the model developed, further testing of tyres considered in this study using the SIM system will be necessary. Testing of other tyre sizes will further allow the model to be expanded, specifically more modern tyres (post 2010) in order to account for the latest tyre technology. The addition of more data points will also make the data statistically more reliable and would allow the models developed in this investigation to be further tested. More data would also result in a reduction in the error of the universal approach with a single function for all tyre widths. In addition to this, the impact on contact stress across the various tyre brands can be determined.

It is furthermore recommended that a 385 tyre with the same “high rib” tread patterns be investigated in order to quantify the accuracy of the developed model based on linear interpolation.

The models can also be expanded to include the observed change in gradient of the uniform stress vs axle load curves at a specific point for all tyre inflation pressures.

The regression models could be expanded to include other tyre parameters, such as profile height and tread pattern to increase the accuracy of the universal function.

Future investigations can also aim to develop models that move away from the assumption of uniform contact stress and instead take into consideration the variation in the contact stress across the contact area.

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