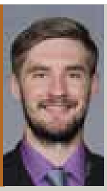
Modelling the vertical uniform contact stress of heavy vehicle tyres



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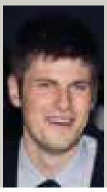

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BACKGROUND

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". The performance-based standards (PBS) or "Smart Truck" pilot project has been operational in South Africa since 2007, and currently approximately 162 vehicles, spread over various industries, are participating in the project.

PBS is a framework of heavy-vehicle regulation, distinct from the more usual prescriptive approach found in many countries. The PBS approach directly assesses desired vehicle performance in terms of safety, stability and road wear, instead of the indirect prescriptive approach. The scheme has significant potential benefits in terms of transport efficiency, road/vehicle safety and the protection of road infrastructure.

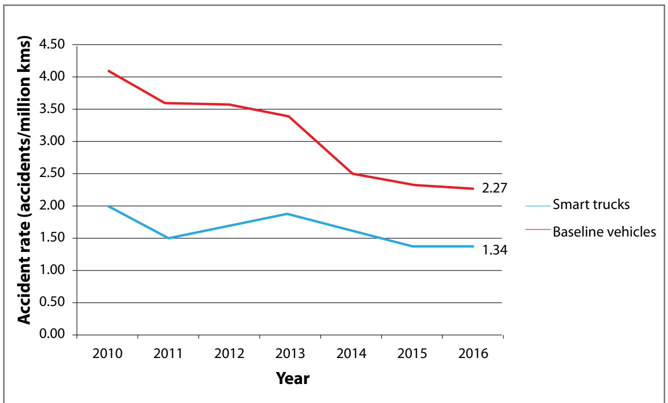

Figure 1: Accident rates for smart trucks and baseline vehicles

By the end of June 2016 approximately 73 million monitored kilometres had been completed by the PBS fleet. The project is showing dramatic improvements from both a safety and efficiency perspective. It is envisaged that, by the end of 2016, the current fleet would have saved a total of approximately 280 000 trips and in excess of 8 million litres of fuel since 2010. There has also been a significant improvement in safety statistics, with baseline vehicles showing a 70% higher crash rate compared to smart trucks (see summary in Figure 1).

The PBS project is also very concerned with the preservation of the national road and bridge infrastructure. Each vehicle is therefore analysed to ensure that it causes less road wear per tonne of payload compared to the baseline vehicle. The vehicle is also subjected to a full bridge load analysis to ensure that the smart truck is not overloaded and does not contribute to failure of various bridge types in South Africa.

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 (Mechanistic Emperical Pavement Design and Analysis Software). Understanding the contact stresses at the tyre–road interface is an important field of study, as this has bearing on the road wear results obtained from road wear assessments.

The tyre–road pavement contact stresses are complex and dependent on numerous variables relating to both the tyres and the operating conditions. 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 therefore 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 is required for a road wear assessment. The one method assumes 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 circular 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

Figure 2: Stress-In-Motion (SIM) measuring pad

Figure 3: Higway rib tread pattern

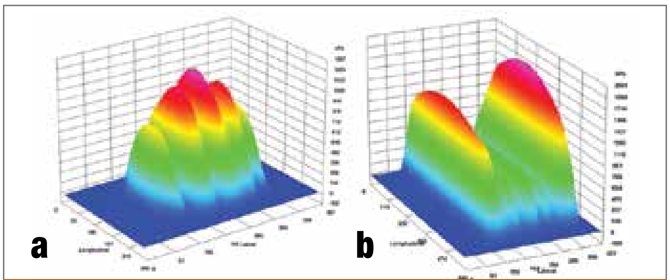

Figure 4: Examples of (a) the "n" shape vertical stress distribution for a heavy vehicle tyre, and (b) the "m" shape vertical stress distribution

Table 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
315/80 R22.5	2 500	590	590	315	514
315/80 R22.5	3 000	740	740	380	469
315/80 R22.5	4 000	850	850	505	657
425/65 R22.5	4 000	600	600	280	428
425/65 R22.5	4 500	700	700	315	514
425/65 R22.5	5 000	795	795	350	547
11 R22.5	2 000	580	580	320	368
11 R22.5	2 500	760	760	400	361

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 triaxial (3D) tyre force/stress distributions (De Beer 1994; 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. An SIM measuring pad testing area consists of 1 020 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 preconditioning 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-rolling (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 the SIM measuring pad is shown in Figure 2.

Research performed at the CSIR (Council for Scientific and Industrial Research) has suggested that the actual uniform contact stress values measured for tyres typically fall somewhere between the two traditional assumptions of uniform contact stress on a circular area as described earlier. This phenomenon is illustrated in Table 1.

From the PBS analyses performed at the CSIR it has been noted that most of the vehicles being studied use the 315/80 R22.5 tyre type, with a number using 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 3. Therefore only this tread pattern was considered during this study.

Currently no single equation exists in order to predict the actual measured uniform contact stress at the tyre–road interface for various tyre types. There is even less success at creating an accurate model for 3D stress distributions at the footprint.

A phenomenon worth mentioning is that generally the contact pattern ("footprint") of a tyre changes from the well-known "n" shape to the "m" shape with increased tyre loading and/or reduced tyre pressure. These "n" and "m" shape patterns refer to the shape of the curve of the peak stresses over the width of the tyre contact area. Examples of "n" and "m" shape distributions are shown in Figure 4.

AIMS OF THE STUDY

The aim was to develop a vertical tyre–road interface stress model in order to estimate the uniform contact stress for three specific tyre types (315s, 385s and 425s).

Three tyres from the Stress-In-Motion (SIM) database were used in the development of the functions necessary to estimate the uniform contact stress at the tyre–road interface. Multivariate linear regression was used to develop the functions for the tyre contact stress. Furthermore, only the "highway rib" tyre tread pattern was considered during this analysis, while all other factors that may influence contact stress were not considered.

The results will be used to increase the accuracy of the road wear simulations performed as part of the PBS project. It can also be used to quantify the effect that over- and underinflated tyres have on the road infrastructure.

PROJECT DESCRIPTION

The TyreStress-Internal application developed by the CSIR was used to access the SIM test data. The entries for 315s, 385s and

Table 2: Errors associated with different equations for three tyre types

Error	315s	385s	425s
Maximum error	6.14%	4.12%	6.02%
Average absolute error	1.19%	1.04%	1.64%

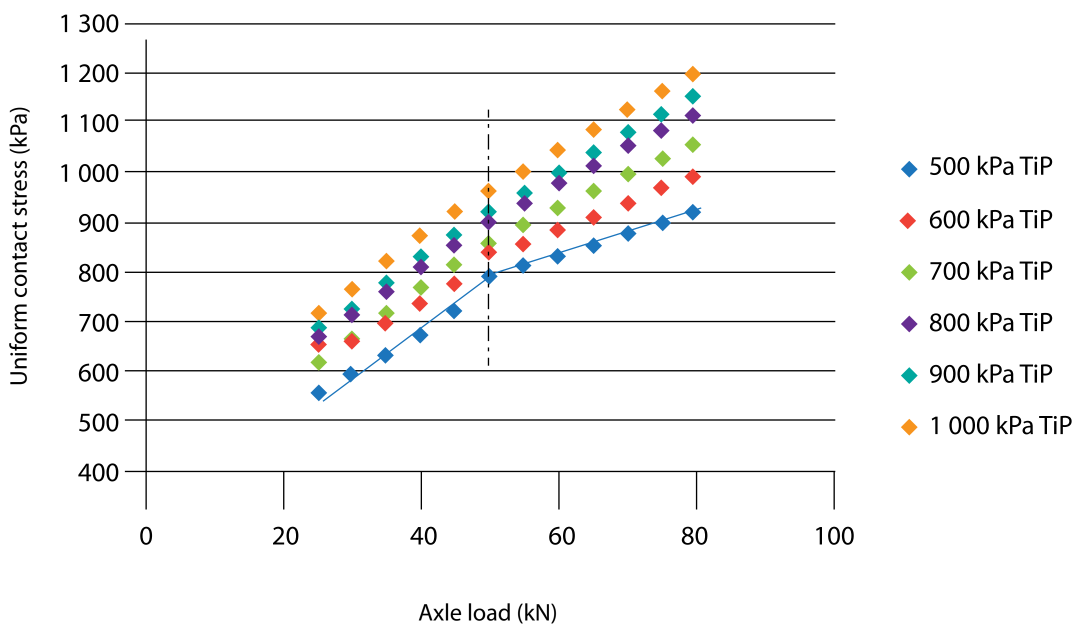

Figure 5: Axle load versus uniform contact stress for Tyre 8 (315) at various tyre inflation pressures (TiP)

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 through visual inspection, as well as 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 database. 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 TiPs and available tyre loads.

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

PROBLEMS ENCOUNTERED AND INNOVATIONS

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.

Of all the entries in the TyreStress-Internal application, one set of tyre data was selected for a 315 and one for a 425 tyre type. Both these tyres were manufactured and tested in 1996.

The model selected to determine the uniform contact stress was the so-called "Equivalent Staggered Diamond", available in the TyreStress-Internal database. 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.

The results illustrating the relationship between the tyre load and the uniform contact stress over a circular area were plotted to visualise the data in order to look for structure contained therein. Figure 5 illustrates the relationship between the axle load and the uniform contact stress at various tyre inflation pressures for Tyre 8 (315).

One unexpected trend is the change in gradient in the curves, as can be seen at a tyre load of 50 kN (Figure 5). On either side of this gradient change the curves follow an approximately straight line. The slope of these curves are, however, different on either side. It is postulated that this change in gradient indicates 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 by results obtained from finite element studies (a similar trend was observed for Tyre 6, but at a different tyre load).

Various models spanning different test regions were investigated in order to obtain the most accurate model/s. After various iterations it was found that the most accurate results were for an operating range of 25 kN to 45 kN vertical tyre load. 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.

It was also found that a universal model, where the tyre width is an input model, had significantly lower accuracies compared to models fitted to each individual tyre. A model was therefore developed for each tyre type.

Multivariate linear regression with a 4th order polynomial produced the lowest average errors for all approaches.

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 15 terms in each of the equations. The errors associated with the different equations are listed in Table 2.

CONCLUSION

Uniform tyre–road interface stress models have been developed for 315, 385 and 425 tyres which accurately predict the average vertical uniform contact stress between the road and tyre surfaces. These equations were developed for the normal operating loading 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 into road wear assessments, as performed by the CSIR, in order to obtain more accurate results. The value and the need for road wear analyses are increasing as the importance and cost to develop and maintain the road infrastructure are better understood. Further work in this field is therefore needed.

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 allow the model to be expanded further, specifically by using modern tyres (post-2010) in order to account for the latest tyre technology. The addition of more data points will also render the data statistically more reliable and would allow the models that were developed in this investigation to be tested further. 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 "highway 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 versus 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 could also aim to develop models which move away from the assumption of uniform contact stress and instead take into consideration the variation in the contact stress across the contact area. The 3D stress state could also be incorporated to take longitudinal effects into consideration.

The PBS project is showing great potential to increase the safety and efficiency of heavy vehicle transport. Continued research on tyre–road stresses is of the utmost importance for the preservation of the South African road infrastructure.

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