Back

STRESS-IN-MOTION (SIM) - A NEW TOOL FOR ROAD INFRASTRUCTURE PROTECTION ?

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Abstract

Aspects of Stress-In-Motion (SIM) as a potential tool for road infrastructure protection are summarized in this paper. Research in South Africa (SA) has led to the local acceptance of SIM data for HV tyres. This paper discuss issues towards the measurement and characterization of multi-dimensional tyre loading and contact stresses of typical HV tyres on SA roads in mechanistic structural road design. The SIM technology is used to capture loading data at the *individual* tyre level in 3D, and a summary is given here of the results of a major demonstration project in SA. Typical SIM data obtained from Heavy Vehicles (HVs), including Total measured vehicle mass, individual tyre mass and typical contact stresses found for a sample of 2 292 HVs (45 165 tyres) on a major National Road 3 (N3) are summarized here. It is suggested that the SIM technology may have potential use in the protection of road infrastructure by improving the multi-dimensional load/contact stress regime between tyres and the road surface in the mechanistic design of road pavements.

Keywords: Stress-in-motion (SIM), Heavy vehicles (HVs), Mass, Load, Contact stresses, Interaction, Pavement, Tyres, Mechanistic design, Strain energy of distortion (SED).

Résumé

Les contraintes en marche (SIM) présentées dans cet article, constituent un outil potentiel utilisable pour la protection des infrastructures routières. La recherche en Afrique du Sud a conduit à l'acceptation des données SIM pour les pneumatiques des poids lourds. Cet article présente les mesures et la caractérisation multidimensionnelle de la charge des pneumatiques et des contraintes de contact des pneumatiques de poids lourds sur les routes sud africaines pour la conception structurelle des routes. La technologie SIM est utilisée le recueil des données de charge 3D au niveau du pneumatique individuel, et les principaux résultats du projet de démonstration sud africain sont présentés dans cet article. Des données typiques SIM de poids lourds, dont le poids total, les différents poids des pneumatiques et les contraintes de contact pour un échantillon de 2292 poids lourds (45165 pneus) sur une grande route nationale 3 (N3) sont présentées ici. La technologie SIM peut servir pour protéger les infrastructures routières en améliorant le régime de contraintes multidimensionnelles au contact entre le pneus et la surface de la route, et donc pour la conception des chaussées.

Mots-clés: Contraintes en marche (SIM), poids lourds, masse, charge, contrainte de contact, interaction pneus/chaussée, conception mécanique, énergie des contrainte de distorsion (SED).

1. Introduction

Road infrastructure protection is one of the main priorities of many developed and even developing countries today. It is generally appreciated as an important asset which is integral with economies of scale worldwide, and therefore need to be protected. Weigh-In-Motion (WIM) technologies have advanced to the point where the road authorities can now get traffic loading information on daily basis, especially on the most important economic roads in a country. In South Africa (SA), a developing country with a total of approximately 750 000 km of roads, of which only 20 percent is currently paved. WIM plays a major role in obtaining relevant information for the engineering management of the asset. From a road pavement design point of view, pavement engineers are faced with many challenges, of which one particular one 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 technique whereby *individual* multi-dimensional (3D) tyre-road contact forces (and hence actual contact stresses) are measured is described. The technology is referred to as Stress-In-Motion (SIM), and may be seen as a next generation of WIM technologies, with specific use in capturing individual tyre (wheel) loads and 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. Tyre-pavement contact stress measurements were carried out on a busy national road (N3) in South Africa from the port of Durban to the inland province of Gauteng. The three-dimensional (3D) tyre-pavement loading and contact stress regimes of 45 165 *individual* tyres were measured using the Stress-In-Motion (SIM) system developed in South Africa. 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. The aim of this paper is to summarise examples of the outputs from the SIM technology which are based on a major research demonstration project completed under the auspices of the South African National Roads Agency Limited (SANRAL) during 2003 on the N3 road. The following are discussed in this paper: SIM in comparison with WIM scales; Total measured (weighted) Vehicle Mass and/or Total measured Combination Mass (TVM/TCM) for 2 292 Heavy Vehicles (HVs); *Individual* tyre mass weights (45 165 tyres); typical tyre inflation pressures on HVs (1 070 tyres); Typical example of SIM measured Vertical Contact Stress (VCS) pattern and a suggestion for enhanced mechanistic-empirical pavement design, based on the concept for Strain Energy of Distortion (SED) as an indication and quantification for road damage from the top down is shown.

2. The traffic loading on the national road N3

There are approximately 253 000 registered heavy vehicles with a TVM/TCM greater than 3.5 tonnes in SA, of which 26 000 are buses (Bosman, 2004). In South Africa there is a move towards classifying 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 the N3 road discussed here, 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 (High) 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 traveling 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 February 2007-October 2007. The N3 is therefore the national road with the highest growth and HV composition in SA (Le Roux, 2007).

3. 3D Tyre-Pavement Contact Stress Measurements on the N3

This paper reports on aspects of an experimental program conducted during 2003, in which the results obtained from the SIM technology were compared with those from a Weigh-In-Motion (WIM) scale (DAW 50) and a Multi-Deck Static scale at the N3 Traffic Control Centre (N3-TCC) near Heidelberg in Gauteng. Although the main function of the SIM technology is to provide information on the 3D tyre-pavement contact stress regime for enhanced road pavement design, this technology can also be used to obtain tyre mass weights, axle mass weights, axle group weights and TVM/TCM. The SIM system was installed in a specially designed test pit near the WIM scale (DAW 50) next to the Multi Deck Static scale in a parallel lane in the north-bound direction of the N3-TCC, northern direction. See Figure 1 showing a HV approaching the SIM scales on the N3-TCC during 2003.

Figure 1 – Typical heavy vehicle (HV Class 1:2:2:2) moving slowly over the SIM device during measurement. Note the two SIM pads each side in front of the tyres.

A useable total of 2 292 HVs, 12 830 *individual* axles and 45 165 *individual* tyres were measured with the SIM over a 6 week period during 2003 at the N3-TCC A manual selection on the quality of SIM data was made per HV, as its tyre loads were captured on the SIM. HVs not correctly positioned over the SIM (see Figure 1) were disregarded in the analysis in this paper. The majority of HVs (77 per cent) incorporated 3 or more axles. For the purposes of statistically comparing the measurements on the SIM device, DAW 50 and Multi - Deck Static scales, paired data sets were used. The validated paired data indicated that the SIM data compares very linearly (with $r^2 \approx$ unity) for the TVM/TCM, axle group mass weights and axle mass weights. Since the SIM results compared very linearly with the DAW 50 and the Multi – Deck Static measurements, the SIM data corresponded almost exactly with the results from both the DAW 50 and Static weighbridges. After a + 6 per cent linear calibration/correction factor was applied, the data in Figure 2 shows an excellent linear (and almost equal, on average) correlations based on the TVM/TCM measured on the SIM, the Multi-Deck Static Scale and the DAW50 dynamic scale for a total of 1 245 HVs (paired data) are shown. It should, however, be noted that the SIM system was primarily designed to capture the 3D tyre-pavement contact stress regimes (i.e. Vertical, Lateral and Longitudinal) and the fact that total mass weights can be obtained per tyre, per axle, per axle group and TVM/TCM is regarded as a bonus. The main reason for the Y-Error of approximately 1.4 tonnes in the case of the SIM is related to the time-based incremental measuring principle that is employed. Only a 10 mm cross section of each tyre patch is measured (De Beer et al, 1997). It is however appreciated that the risk of this measurement principle is a relatively large variability of the mass weights owing to damaged tyres, different tread patterns, tyre make, etc., by comparison with the weights determined on normal WIM scales which support the full tyre patch during measurement.

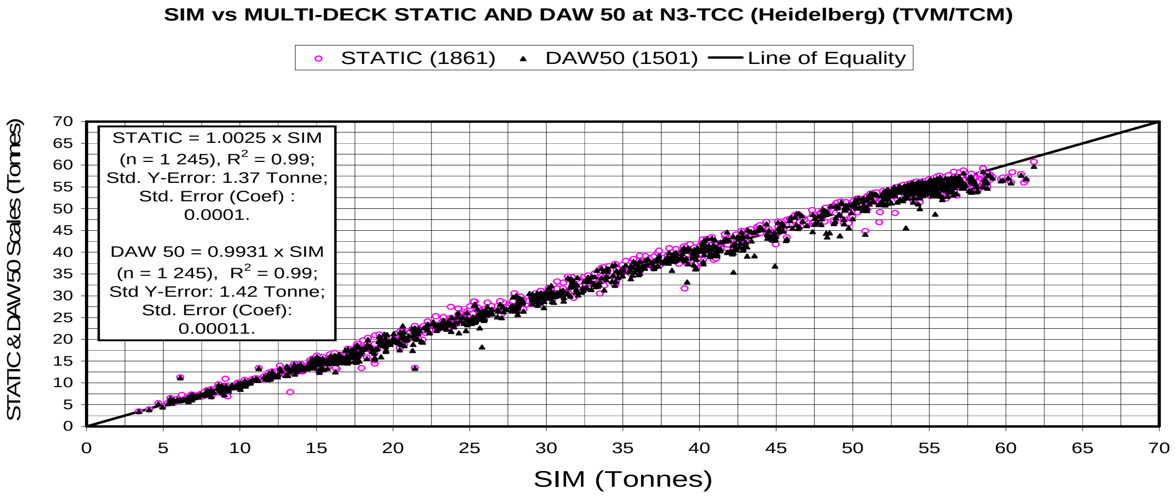

Figure 2 – Comparision of TVM/TCM measured on the SIM, Multi-Deck Static Scale and the DAW 50 dynamic scale, after a +6 per cent linear correction on the SIM data

3.1 Composition of HV Class of the measured population during 2003

The composition of the measured HV population (2 292 HVs), from the N3 highway that went over the scales during the testing period were also recorded. Approximately 45 per cent of the HVs were of the 1:2:2:2 Class. Note that the 1:2:2:2 Classification used here represents a truck with one steering axle, and three tandem groups (Nordengen et al, 1991).The majority of HVs had more than 3-axles (approximately 77 per cent). Figure 3 indicates the TVM/TCM of all the 2 292 HVs measured. It is interesting to note that, for the HV population tested, three distinct peaks (or approximate "mode-values") are observed to occur at 15 tonnes, 29 tonnes and 51 tonnes.

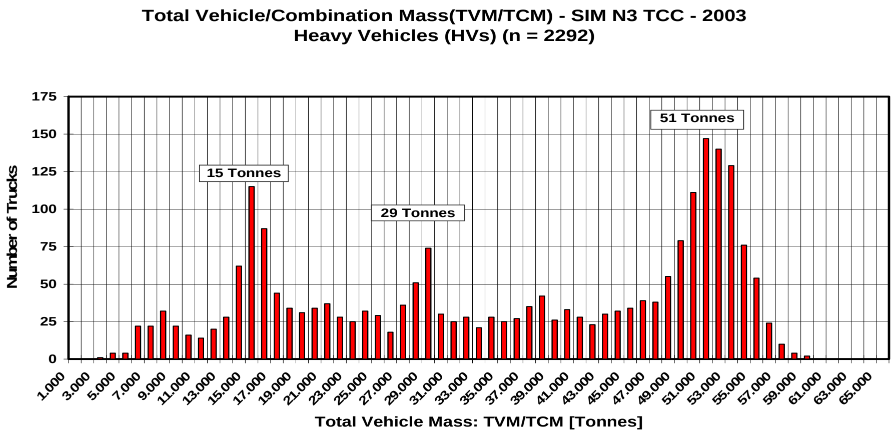

Figure 3 – Histogram (and modes) of the 2 297 HVs measured based on TVM/TCM.

3.2 Individual Tyre Mass Weights

The histograms of *individual* tyre mass weight data for 45 165 tyres are shown in Figures 4. Typical Gaussian (normal) distributions were obtained for the tyre mass weights, and Figure 4 indicates that the tyres on the steering axles of all the HVs measured carried an average mass weight of approximately 1.2 tonne per tyre *more* than that carried by the other tyres. It was found that most of the tyres carried a mass weight of less than 4 550 kg.

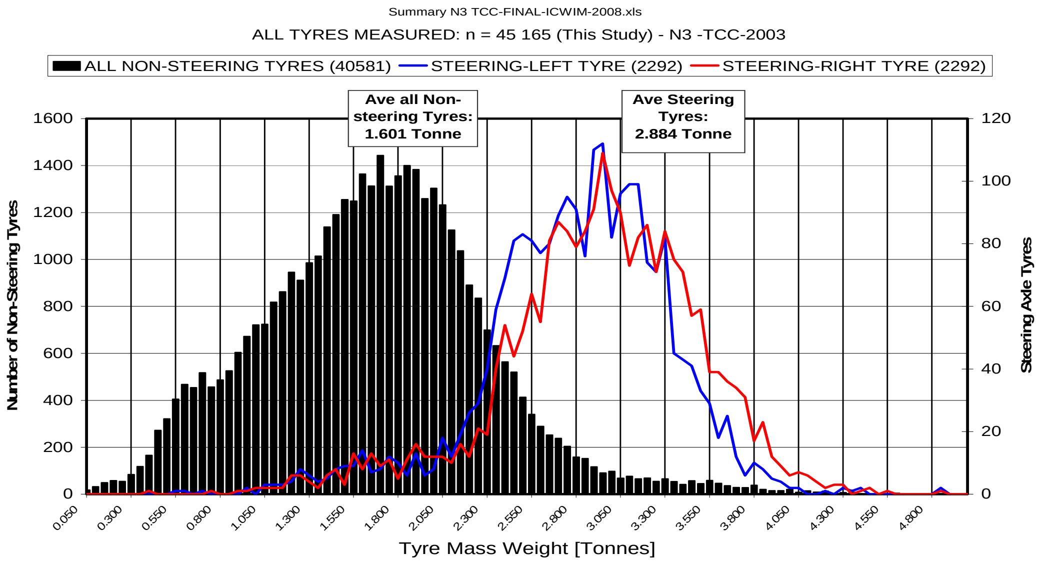

Figure 4 – Histogram of individual tyre loading of the 45 165 tyres tested.

3.3 Tyre Inflation Pressures

Typical tyre inflation pressures of HVs tyres travelling on the same route (N3) are shown in Figure 5, from another study (Morton et al, 2004). The inflation pressures are also normally distributed, and typically range between 400 kPa and 1 100 kPa. The inflation pressures of both tyres on the steering axles were approximately 100 kPa higher than those of the rest of the tyres measured. During October 2003 a sample of typical running tyre temperatures was measured at this site, which indicated average temp of 34 degree C, ranging from 12 to 60 degree C, with maximum up to 81 degree C.

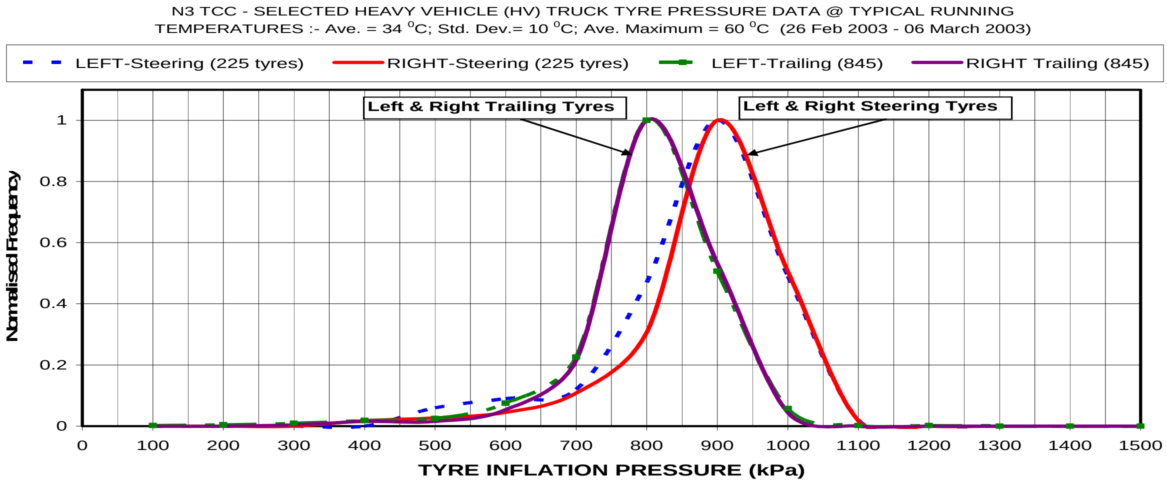

Figure 5 – Tyre inflation pressures of HVs typically found on this road (N3) measured at typical average running temperatures of approximately 34 ºC (Oct 2003).

4. Measured Contact Stresses

4.1 Typical SIM results - Vertical Contact Stresses

In this section the results of only the measured vertical contact stresses are discussed. For approximately 45 165 tyres measured over a period of 29 days, the *maximum* vertical contact stress varied between 1 540 kPa and 2 240 kPa (mean = 1 820 kPa, std. deviation = 27 kPa) and the maximum tyre mass weights varied from 1 935 kg to 5 848 kg (mean = 4 012 kg, std. deviation = 908 kg), for this study. In Figure 6 the vertical contact stress contour (i.e. footprints) of all 30 tyres of a typical heavily loaded 8-axle interlink HV (SIM Test H1029; 1:2:2:3 HV with TCM = 53.37 tonnes, in this case) is illustrated, as an example. The individually measured tyre mass weights are also shown for each tyre. It is interesting to note that the maximum mass weights and maximum vertical contact stresses were found for the tyres on the steering axle. In this example the steering tyre mass weights were 3.478 tonnes and 3.562 tonnes, respectively, and the maximum vertical stress for the two tyres 1 130 kPa and 1 150 kPa, respectively – see Figure 6.

4.2 Shape of SIM measured vertical contact stress patterns

For pavement design purposes it is important to take the shape and distribution of the contact stress into consideration as was indicated earlier studies (De Beer et al, 2004a, 2004b; De Beer, 2006). Typically, normally loaded and correctly inflated tyres produce the "n-shape" profile – (see Figure 8 later). For the test series described in this paper, most of the steering tyres produced "n-shape" patterns for the vertical contact stresses. Also, as mentioned earlier, these tyres also carried much greater mass weights than did the other HV tyres (on average approx. 1.2 tonnes more). [Perhaps this is an indication that the steering tyre loading and contact stress conditions should be used for a typical "pavement design axle", since this axle appears to be the critical axle on heavy vehicles such as the HVs studied here.] From the above illustrations it is clear that the vertical contact stress footprints obtained from real world HVs are *non-circular* and *non-uniform*. It is considered that this non-uniformity should be incorporated, especially in the design of pavements with relatively thin asphaltic surfaces (< 100 mm), including surfacing seals (De Beer et al, 2004a, 2004b, De Beer, 2006). It is this author's opinion that "shape and profile, or pattern" of the contact stress regime should therefore be introduced during the design stage of pavements and pavement surfacings. In addition, the effects of lateral and longitudinal stresses can be significant at shallow depths, as was demonstrated by previous research on this topic (Uzan et al, 1987; Jacobs, 1995; Himeno et al, 1997; Myers et al, 1999, 2001; Roque et al, 1998, 2000 De Beer et al, 2004b; Milne et al, 2004). Figure 7 illustrates the cumulative frequency plots of all 30 tyres of a 1:2:2:3 HV (SIM Test H1029 indicated in Figure 6). Amongst others, the figure indicates a wide spread of vertical contact stresses, whose maximum (or peak) stresses range from 420 kPa (Axle 8, left inner tyre) to approximately 1 175 kPa Axle 1, right tyre). This spread is typical of most of the tests carried out at this site and could potentially guide probabilistic mechanistic pavement design in future, by using each tyre mass weight (or loading/stresses) as inputs.

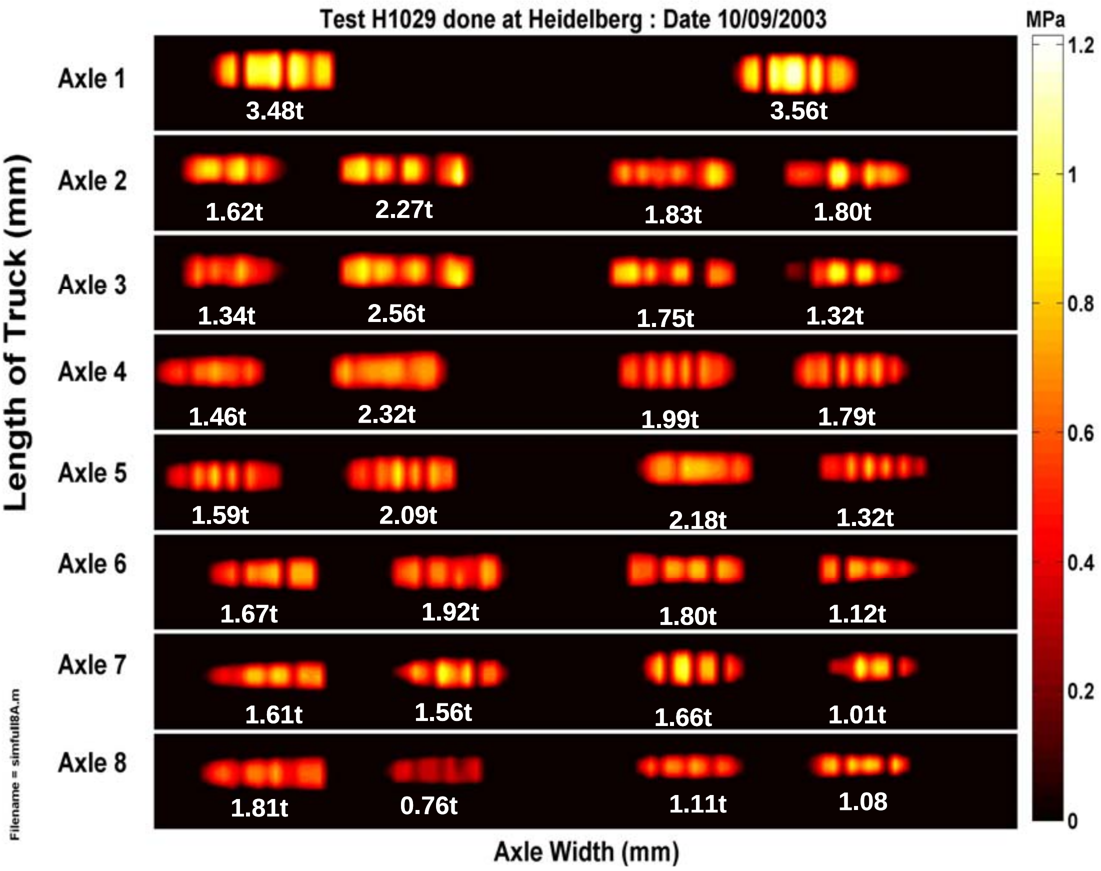

Figure 6 - SIM Test H1029: Vertical contact stress footprints of all 30 tyres of a 1:2:2:3 8-axle HV (TCM = 53.37 tonnes) at N3-TCC (not to scale).

5. Suggestions for Mechanistic Flexible Pavement Design

During 2006, the author suggested to re-consider the modeling of tyre-road surface interaction by using the measured SIM data, of which examples as were also discussed by others (Blab, 1999; Blab and Harvey, 2002; Ullidtz, 2002; Myers et al, 1999; Roque et al, 1998).

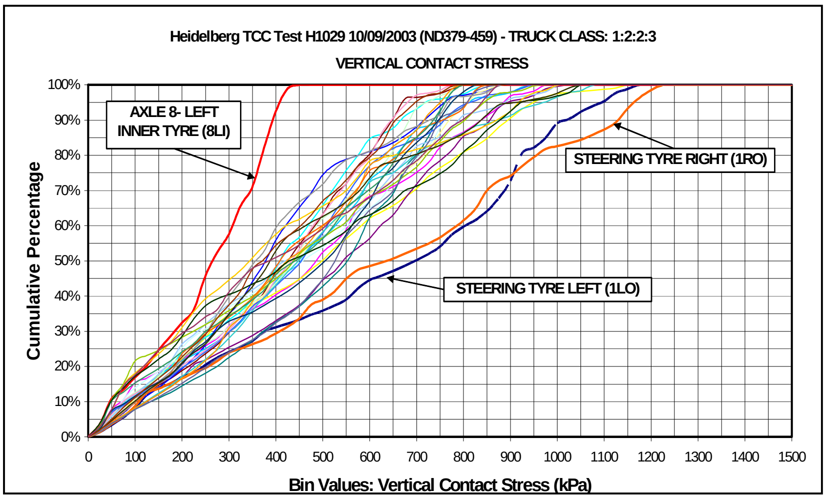

Figure 7 – Measured vertical contact stresses from the 30 tyres of the HV shown in Figure 6.

In this paper a further example is given to study the "distortional damage potential" with-on and with-in asphalt layers based on the Strain Energy of Distortion (SED) described by Timoshenko et al, 1951. This principle was also used earlier pavement studies (De Beer et al, 1997; De Beer, 2006). The SED for a 425/65 R-22.5 wide base tyre was calculated on top of a 3 layer flexible pavement The GAMES (General Analysis of Multilayered Elastic Systems by Maina et al (2004), software caters also for horizontal surface loadings in addition to vertical surface loadings (Figure 8a), which was included in this analysis. An illustration of the calculated SED as a response from the pavement surface is shown in Figure 8b. This suggests that SED based on principle stresses might be used for consolidation, or rutting associated with volume change in pavement layers, whereas SED based on normal x, y, z - stresses (i.e. with shear components) may be a better parameter for shear distortion (rutting at constant volume) as was indicated earlier (De Beer et al, 1999).

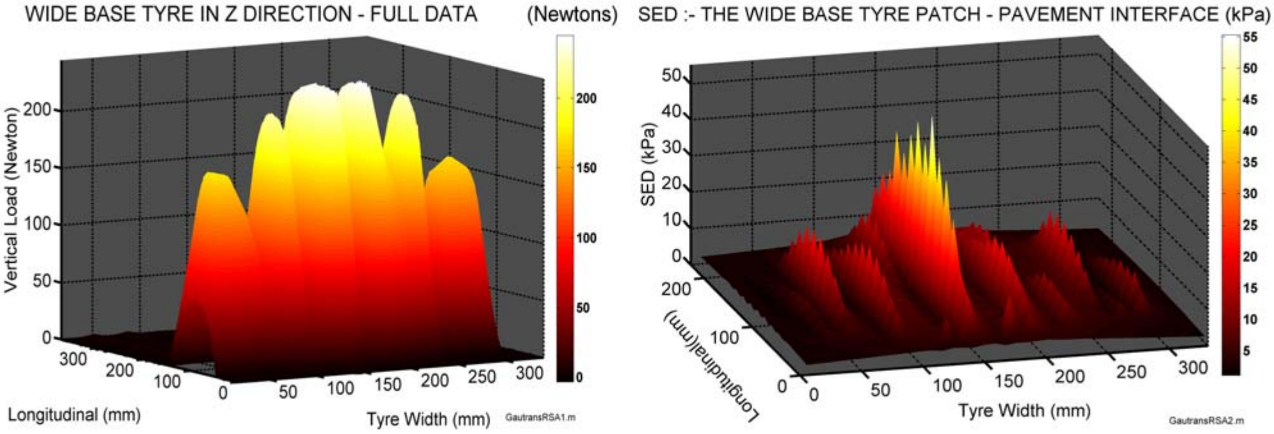

Figure 8 - Left (a) Measured Vertical Contact Loads from SIM ("typical "n-Shape", and Right (b) Strain Energy of Distortion (SED) under the 425/65 R22.5 wide base HV tyre.(Our Dr J Maina and Mr C Fisher is acknowledged for these figures).

6. Summary and Conclusions

Aspects of Stress-In-Motion (SIM) technology as a potential tool for road infrastructure protection are summarised in this paper. The research discuss issues towards the measurement and inclusion of multi-dimensional loading and contact stresses of typical HV tyres on SA roads in mechanistic structural road design. In summary, the SIM technology was used here to capture loading data at the individual tyre level in 3D during a major demonstration project in SA. The typical SIM data obtained from 2 292 HVs, including Total Vehicle/Combination Mass (TVM/TCM), 40 165 *individual* tyre mass and typical contact stresses found on a major National Road 3 (N3). It is concluded that the SIM technology may have potential use in the protection of road infrastructure by improving the multi-dimensional load/contact stress regime between tyres and the road surface in the mechanistic design of road pavements by utilizing the SED, computed from SIM measurement for each individual tyre of HVs.

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