

COMPARISON OF CONTACT STRESSES OF THE TEST TYRES USED BY THE 1/3RD SCALE MODEL MOBILE LOAD SIMULATOR (MMLS3) AND THE FULL-SCALE TEST TYRES OF THE HEAVY VEHICLE SIMULATOR (HVS) – A SUMMARY

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ABSTRACT

This paper summarises the results of a study in which the maximum vertical contact stresses of the 1/3rd scale test tyres of the Model Mobile Load Simulator (MMLS3) were compared with those measured for three types of full-scale test tyres of the Heavy Vehicle Simulator (HVS). The comparative tests were done using the Stress-In-Motion (SIM) device designed to capture three-dimensional (3D) tyre-pavement contact stresses on a relatively rough-textured test surface. As it is generally accepted that these stress conditions within the moving tyre contact patch are quite complex, a single parameter of the vertical stresses measured for the different test tyres was selected for the comparison. This parameter, referred to as the Maximum Vertical Contact Stress (MVCS) indicated, on average, that it increased linearly with tyre inflation pressure for both types of the 1/3rd scale MMLS3 test tyres and full-scale test tyres. However, it was found that the MVCSs for the Diamond patterned square profile 1/3rd scale tyres of the MMLS3 were, on average, much lower than those of the full-scale test tyres as they represented, at most, only 52.5 per cent of those measured for the 11R22.5 (full-scale HVS) test tyre, 37.5 per cent for the single 315/80 R22.5 (full-scale HVS) test tyre, and 12.5 per cent and 20 per cent respectively respectively for the smooth and rough-texture tests on the 12R22.5 (full-scale HVS) test tyre. Earlier studies of vertical contact stresses of the test tyres of the MMLS3 by Sime M & Ashmore SC, (1999), Epps Martin et al (2000) and Doupal et al (2002) that were conducted with different stress measuring devices reported higher vertical contact stresses at the upper level of tyre inflation pressures. It is therefore recommended that the influence of test surface characteristics and the impact on SIM measurements of HVS and MMLS3 tyres be investigated in greater detail in future similar studies. It is nevertheless strongly recommended that the foregoing be incorporated into MMLS3 and HVS comparative and/or individual testing programs (and protocols) to permit a *more rational interpretation* of test data from both these devices relative to structural road pavement performance issues, especially on the surface of flexible road pavements.

1. INTRODUCTION

The problem that was addressed in this study was to quantify the differences, if any, between the tyre contact stresses of the 1/3rd scale test tyres of the Model Mobile Load Simulator (MMLS3) and those of the full-scale test tyres on the Heavy Vehicle Simulator (HVS). This study represents the most comprehensive investigation of the contact stresses under the MMLS3 tyres. Earlier studies of vertical contact stresses under MMLS3 test

tyres were reported by Sime and Ashmore (1999), Epps-Martin, et al (2002) and Doupal et al (2002). This information was urgently needed to assist with the evaluation of test results in a recent comparative test program initiated by the Gauteng Department of Public Transport, Roads and Works (GDPTRW) (Gautrans) using both the MMLS3 and the HVS (Sampson and Sadzik, 2004). As the MMLS3 is a 1/3rd scale device it is, in principle, a cheaper option for Accelerated Pavement Testing (APT) than a full-scale test device such as the HVS. (See Table 1 for a nominal comparison of the devices.) However, users should be aware of the physical differences between scaled-down and full-scale devices in terms of input and output of test results, such as loading, inflation pressure, speed, plastic deformation (or rutting), cracking and also elastic responses produced by these devices. This is considered *fundamentally* important for the correct and *more rational way of data interpretation* during comparative testing, as well as for individual testing protocols and test programs for these devices.

Table 1. Characteristics of MMLS3 (highway applications) and HVS Mk IV⁺

Characteristic	MMLS3	HVS
Nominal Constant Tyre Loading Range (kN)	1.9 to 2.9	30 to 205 (Dual, Single, Aircraft)
Footprint area (approximately), depending on tyre type, loading and inflation pressure (cm ²)	34 to 45	380 to 881
Inflation pressure (kPa) @ 25 °C	560 to 860	420 to 1 000
Nominal Speed Ranges: (km/h)	Simulated: 3 to 26 (Actual 1 to 8.67)	6 to 12
Approx. wheel load repetitions per hour (rep/hr)	7 200	Uni-directional: 660, and Bi-directional: 1 300.

The scope of this paper is limited to summarising the differences found between the vertical tyre-pavement contact stresses of the 1/3rd scale and those of the full-scale test tyres of the both the MMLS3 and the HVS devices. The Stress-In-Motion (SIM) technology was used for quantification of the 3D contact stresses under moving pneumatic tyre loads, from which the Maximum Vertical Contact Stress (MVCS) parameter was selected for comparative purposes in this study. The MVCSs indicated, on average, that they increased linearly with tyre inflation pressure for both types of 1/3rd scale and full-scale test tyres. However, it was found that the MVCS for the Diamond patterned square profile (D-tyre) 1/3rd scale tyres of the MMLS3 were, on average, much lower than those of the full-scale test tyres and represented, at most, only 50 per cent of those measured for the 11R22.5 (HVS) test tyre, 35 per cent for the single 315/80 R22.5 (HVS) test tyre, and 20 per cent for the 12R22.5 (HVS) test tyre. Similar findings were made using a simulated artificial smooth test surface on the SIM device. Details of the tests and results are given in Technical Memorandum CR 2005/30 (see De Beer *et al*, 2006). It is therefore strongly recommended that the foregoing be incorporated into MMLS3 and HVS comparative and/or individual testing programs and protocols to permit *a more rational interpretation* of test data from both these devices relative to structural road pavement performance issues, especially on the surface of flexible road pavements.

2. APPROACH AND METHODOLOGY

2.1 Approach

The approach for this study was to perform actual 3D tyre contact stress measurements for the test tyres under consideration using the locally developed SIM technology, from which one parameter, Maximum Vertical Contact Stress (MVCS) was selected as a basis for comparison between the different tyres. It is accepted that other parameters may be used instead but, as a start on these comparative type studies, the MVCS was selected as it proved to be an important parameter in earlier studies for tyre pavement contact stresses (De Beer *et al*, 1997). The approach followed was:

- Perform the first study (referred to as S1) using the MMLS3 with different tyre types, viz: Longitudinal round profile (L-tyre) and a Diamond square pattern (D-tyre) on a normal rough-textured SIM surface;
- Based on a review of the results from the S1 study by Hugo *et al* (2005) and Moloto (2006) a second study (S2) was undertaken. Only 4 x D-tyres were used on the MMLS3. Tests were done on the rough-textured SIM surface, as well as on an artificially smooth surface on the SIM device; comprising an aluminium plate 1mm thick directly on the pins of the SIM device;
- Perform studies on the full-scale test tyres of the HVS, on both the rough-textured SIM surface as well as on the artificial smooth test surface, and
- Summarise comparative data between the 1/3rd scale MMLS3 tyres and three types of full-scale HVS tyres for both rough-textured and smooth-textured test surfaces¹.

2.2 The following methodology was used in this study:

- MMLS3 testing was carried out according to MMLS3 protocols on the normal rough-textured SIM test surface with 2 x L-tyres and 2 x D-tyres at three actual speeds, i.e. 1 km/hr; 4.33 km/hr and 8.67 km/hr. Two test series were completed, viz: S1 and S2. See Table 2 for a summary of the test matrices used. A total of 215 tests were done during both the S1 and S2 test series; See also Figures 1 to 3.
- MMLS3 testing was carried out on a relatively smooth artificial SIM surface using a thin and smooth aluminum plate between the test tyre and the SIM device. See Figure 4. Only the 4 x D-tyres were used for this test. The tests were carried out according to the MMLS3 protocol at three actual speeds, i.e. 1 km/hr; 4.33 km/hr and 8.67 km/hr at three tyre inflation pressure levels, i.e. 700 kPa, 800 and 860 kPa and at one load level (2.7 kN). A total of 27 tests were completed in this case.
- Data from previous HVS tests on the SIM device were summarised – See Table 2 (from De Beer *et al*, 1999, 2005), and new HVS tests were carried out on two selected types of tyres. (See Table 3);
- Data reduction and final comparative data analyses were done and the outcomes were reported.

¹ The relatively “rough-textured” and relatively “smooth” test surfaces are *assumed* to represent two different kinds of road surface textures. The rough-textured surface is the SIM surface as designed (See Figures 2 and 3), and the smooth surface was created using a smooth aluminium plate on top of the SIM device during testing (See Figure 4).

Table 2. Summary of SIM tests completed for both the MMLS3-SIM test series (S1 and S2) – on normal rough-textured SIM surface.

Series S1 and S2 testing (MMLS3 configuration:- S1: 2 x L-tyres & 2 x D-tyres/S2: 4 x D-tyres)										
Total Number of Tests (S1/S2)	MMLS3 Load 1.8 kN			MMLS3 Load 2.7 kN			MMLS3 Load 2.9 kN			Inflation Pressure (kPa) (S1/S2)
	0.278 m/s	1.204 m/s	2.407 m/s	0.278 m/s	1.204 m/s	2.407 m/s	0.278 m/s	1.204 m/s	2.407 m/s	
27/26	3*	3	3	3	3	3	3	3	3	400/520
27/27	3	3	3	3	3	3	3	3	3	520/700
27/27	3	3	3	3	3	3	3	3	3	700/800
27/27	3	3	3	3	3	3	3	3	3	800/860
215	Grand total of number of tests completed (S1 & S2)									
1 432	Grand total of number of tests processed (S1 & S2) (Total of all tests on all 4 tyres)									

* Minimum of 3 repeat measurements for each load/inflation pressure/speed condition per tyre. Owing to the higher speeds of the MMLS3, more than 3 repeats per tyre were captured and analysed, which resulted in the high number of tests processed in this study.

Table 3. Summary of SIM tests completed for the three types of HVS tyres.

HVS Load (kN)	Cold Inflation Pressure (kPa)							
	420	520	620	650	720	800/825*	950	1000
20	na/na/na	na/na/3; na/3	na/na/3	na/na/3	na/3/3	na/3/3	na/3/3	na/3/3; na/3
30	3/na/na	3/3/3;3/3**	3/3/3	na/na/3	3/3/6; 3/na	3/3/3	na/3/3	na/3/3; 3/3**
40	3/na/na	3/3/3; 3/na	3/3/3	na/na/3	3/3/3; 3/na	3/3/6	na/3/6	na/3/3; 3/na
50	na/na/na	na/na/3; na/3	na/na/3	na/na/3	na/na/3	na/na/3	na/na/3	na/na/3; na/3
70	3/na/na	3/3/na	3/3/na	na/na/na	3/3/na	3/3/na	na/3/na	na/3/na
80	na/na/na	na/3/na; 3/na	na/3/na	na/na/na	na/3/na; 3/na	na/3/na	na/3/na	na/3/na; 3/na
100	na/na/na	3/3/3	3/3/3	na/na/3	3/3/3	3/3/3	na/3/3	na/3/3

Note: na = test *not* done. The “3/3/6” refers to the number of tests done on the three different types of HVS tyres: 11R22.5/12R22.5/315/80 R22.5”, i.e. 3 tests on the dual 11R22.5 tyre, 3 tests on the dual 12R22.5 tyre and 6 tests on the wide base 315/80 R22.5 tyre. ***Bold Italic = Number of HVS tests on artificial smooth SIM surface, i.e. 12R22.5/315/80 R22.5 tyres only.***

* Only for wide base tyre type 315/80 R22.5; ** Tests done at load = 35 kN, on single tyre 315/80 R22.5;



Figure 1. MMLS3 on the SIM pad at GDPTRW, Koedoespoort facility.



Figure 2. Close-up: 1/3rd scale D-tyre of MMLS3 on the rough-textured SIM surface (pad).



Figure 3. HVS full-scaled dual tyres on the rough-textured SIM surface.

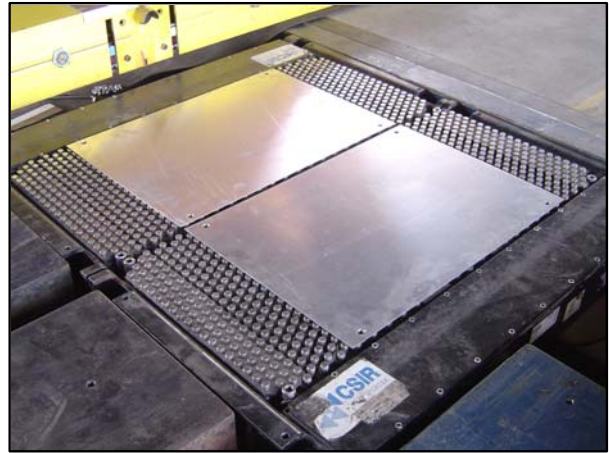


Figure 4. Artificial smooth plate on the SIM surface, before full-scale testing.

3. RESULTS AND DISCUSSION - LOADS AND SPEEDS

3.1 Summary of Results found on the rough-textured SIM surface

3.1.1 S1- Data Series

Two (2) x L-tyres and two (2) x D-tyres were used in series in a single MMLS3 configuration. This also enabled comparative data for these two 1/3rd scale tyres to be obtained. In summary, the following was found (See Table 4):

- 2 x L-Tyres: The measured speed data on the SIM showed a logical increasing trend by comparison with the increasing input speeds from the MMLS3. The average SIM speed was 3.49 per cent higher than that of the MMLS3, with a Coefficient of Variation (CoV) of 1.7 over the range of four (4) inflation pressures and the three (3) tyre load levels of the MMLS3.
- 2 x L-Tyres: The measured load data on the SIM showed a variation, by comparison with the input load from the MMLS3, the SIM loading being on average 7.51 per cent (CoV= 20.6 per cent) *greater* than the MMLS3 input load of 1.8 kN, and 20.14 per cent

(CoV = 12.3 per cent) *lower* in the case of the MMLS3 load level of 2.7 kN, and 9.76 per cent (CoV = 12.1 per cent) *lower* at the 2.9 kN MMLS3 load level. This was observed at all four inflation pressure levels tested during S1. In this case the measured loading was up to 25 per cent *lower* at an input load of 2.7 kN (with CoV = 11.9 per cent) at a tyre inflation pressure of 700 kPa.

- 2 x D-Tyres: The measured speed data on the SIM showed a logical increasing trend by comparison with the increasing input speeds from the MMLS3. The average SIM speed was 3.78 per cent higher, with a Coefficient of Variation (CoV) of 1.9 over the range of four (4) inflation pressures and the three tyre load levels of the MMLS3.
- 2 x D-Tyres: The measured load data on the SIM showed a variation trend similar to that of the Longitudinal tyres, with the SIM loading being on average 3.72 per cent (CoV= 2.9 per cent) *greater* than the MMLS3 input load of 1.8 kN, and 5.89 per cent (CoV = 3.0 per cent) *lower* in the case of the MMLS3 load level of 2.7 kN, and 8.86 per cent (CoV = 3.0 per cent) *lower* at the 2.9 kN MMLS3 load I. This was observed at all inflation pressure levels tested during S1. In this case the measured loading was up to 12 per cent *lower* at an input load of 2.9 kN (with CoV = 1.2 per cent) at 700 kPa.

3.1.2 Discussion on S1 test series

The relatively large variations in measured speed and loading found, especially with the L-tyres, led to a second study (S2) being conducted in order to verify some of the initial findings. During the S2 test series the reference for speed measurement on the SIM was changed from a “dynamic” reference directly on the MMLS3 test tyre, to a “rigid” reference on the wheel-bogie of the MMLS3. The SIM speed device was also re-calibrated against the high-precision laser system at the CSIR (De Beer *et al*, 2006).

Table 4. Summary Statistics of the S1 and S2 test series on MMLS3 speed and loading (This study).

SIM Measurements (S1 & S2)			AVERAGE DIFFERENCE - @ MMLS3 LOAD (%)			CoV - @ MMLS3 LOAD (%)		
Test Series and Tyre Type	Average Difference-Speed (%)	CoV (%)	1.8 kN	2.7 kN	2.9 kN	1.8 kN	2.7 kN	2.9 kN
S1-2 x L-tyre	3.49	1.7	7.51	-20.14	-9.76	20.59	12.31	12.05
S1-2 x D-tyre	3.77	1.9	3.72	-5.89	-8.86	2.93	3.02	3.03
S2-4 x D-tyre	0.65	1.2	-5.21	-13.04	-10.85	1.93	1.27	2.06

3.1.3 S2-Data Series

During the S2 test series, only the normal 4 x D-tyres were used in a single MMLS3 configuration. The following was found:

- 4 x D-Tyres: The measured speed data for the SIM showed a logical increasing trend by comparison with the increasing input speeds from the MMLS3. The average SIM speed was 0.65 per cent higher, with Coefficient of Variation (CoV) of 1.2 over the range of four (4) inflation pressures and three tyre load levels. Note the improvement of

the SIM measured speed values after changing from “dynamic-tyre reference” to a “rigid reference” method.

- 4 x D-Tyres: The measured load data for the SIM showed somewhat lower measured load values for all three load levels of the MMLS3 (i.e. 1.8 kN, 2.7 kN and 2.9 kN), with averages of 5.21 per cent (CoV = 1.9 per cent), 13.04 per cent (CoV = 1.3 per cent) and 10.85 per cent (CoV = 2.1 per cent), respectively. This was observed for all four inflation pressure levels tested during S2. In this case the measured loading was up to 14 per cent *lower* at an input load of 2.9 kN (with CoV = 1.2 per cent) at 700 kPa.

3.1.4 Discussion on S2 test series

During S2 test series, with the new “rigid” speed referencing system, a great improvement in speed measurement with the lowest variation (CoV) was observed.(See Table 4.)

Although all the loadings measured on the SIM with the 4 x Diamond tyres were lower than the three input loads from the MMLS3 during S2, they were, however, accompanied, by relatively low CoVs (less than 2 per cent), by comparison with those in the S1 test series. The under-recording of the loading is believed to be related to the following two main possibilities:

- Incorrect load calibration of the load cell of the MMLS3, especially in the light of relatively less under-recording for the 2 x D-tyres during the S1 testing; and
- MMLS3 tyre-SIM surface interaction, especially on the relatively rough-textured SIM test surface;

In order to address the second issue, an additional special study with a MMLS3 load of 2.7 kN at a tyre inflation pressure of 700 kPa was done on an artificial smooth surface placed on the SIM surface. Hugo *et al* (2005) and Moloto (2006) had shown the measured vertical load and related vertical contact stress was affected by the nature of the contact surface and the method of measurement. Accordingly the S2 test series included trafficking on an artificial smooth surface of an aluminium plate 1 mm thick on the measuring pins of the SIM device. The results are summarised in the next section. The detailed study of the effect of the artificial SIM surface on the scaled-down MMLS3 tyres is discussed in De Beer *et al* (2006).

3.1.5 Summary of MMLS3 load and speed data from on the artificial smooth surface²

In general the load results of tests carried out with the smooth plate on top of the SIM device were found to be somewhat higher than the MMLS3 input loading of 2.7 kN. These loads were approximately 27 to 30 higher than the 2.35 kN load measured on the normal SIM surface. In addition, the use of surfaces relatively smoother than the original rough-textured SIM surface resulted in lower CoVs for the tyre loading. It is believed that the main reasons for the above, include, amongst others:

- Potential higher loads as a result of the thickness plate on top of the SIM surface;
- Elimination of the intrusion of rubber into the gaps between pins limiting contact with the active pins (bridging by the smooth plate on top); and
- Elimination of tyre tread pattern effect (smoothing effect of smooth plate on top) that may cause a reduced loading on the active pins (load spreading by the bridging effect of the plate);

It was further found that the use of smooth surfaces had virtually no effect on the average measured speeds by comparison with the average speed measured on the normal rough-textured SIM surface.

² Plates with longitudinal and lateral grooves were also included in detailed study (De Beer *et al*, 2006)

4. MAXIMUM VERTICAL CONTACT STRESSES (MVCSS)

4.1 General findings:

Details of the 3D tyre-pavement contact stress data are described in De Beer *et al*, (2006).

In this paper only the Maximum Vertical Contact Stress (MVCS) data for the 1/3rd scale MMLS3 D-tyre and three full-scale test tyres on the HVS are compared. The three radial tyre types on the HVS included: a 11R22.5 dual tyre set; a 12R22.5 dual tyre set and a 315/80 R22.5 single tyre. For the HVS tyres, SIM testing was done on both the rough-textured SIM surface and the relatively smooth surface (as in the case of the MMLS3 testing described above). The detailed SIM measurements on these full-scale tyres are described in De Beer *et al*, (1999, 2005, 2006). Amongst others, the following important findings were made:

- The MVCS increased with increased tyre inflation pressure, for both the 1/3rd scale and full-scale test tyres;
- The average MVCSSs of the HVS test tyres were roughly 50 per cent higher than those found for the D-tyre of the MMLS3 for both rough-textured and smooth test surfaces (see Figure 5); and
- On average, the MVCSSs for the relatively smooth test surface were found to be 25 to 30 per cent higher than those for the HVS tests tyres. (See Figure 5).

Based on the results of these tests on artificial surfaces, the following conclusions can be drawn:

- The contact surface texture directly influences the total load and vertical stress results as measured with the SIM device; and
- Tyre intrusion into the pin surface occurs, which may be limited by placing smooth plates on top of the current SIM device, if so desired.

As mentioned before, it was noted that the earlier studies by Epps Martin *et al* (2000) and Doupal *et al* (2002) that were conducted with different devices, reported higher contact stresses at the upper tyre inflation pressures. It is therefore recommended that the surface characteristics of test surfaces be investigated in greater detail in future similar studies.

The average MVCS data for both the rough-textured SIM surface and the relatively smooth test surface are illustrated in Figure 5.

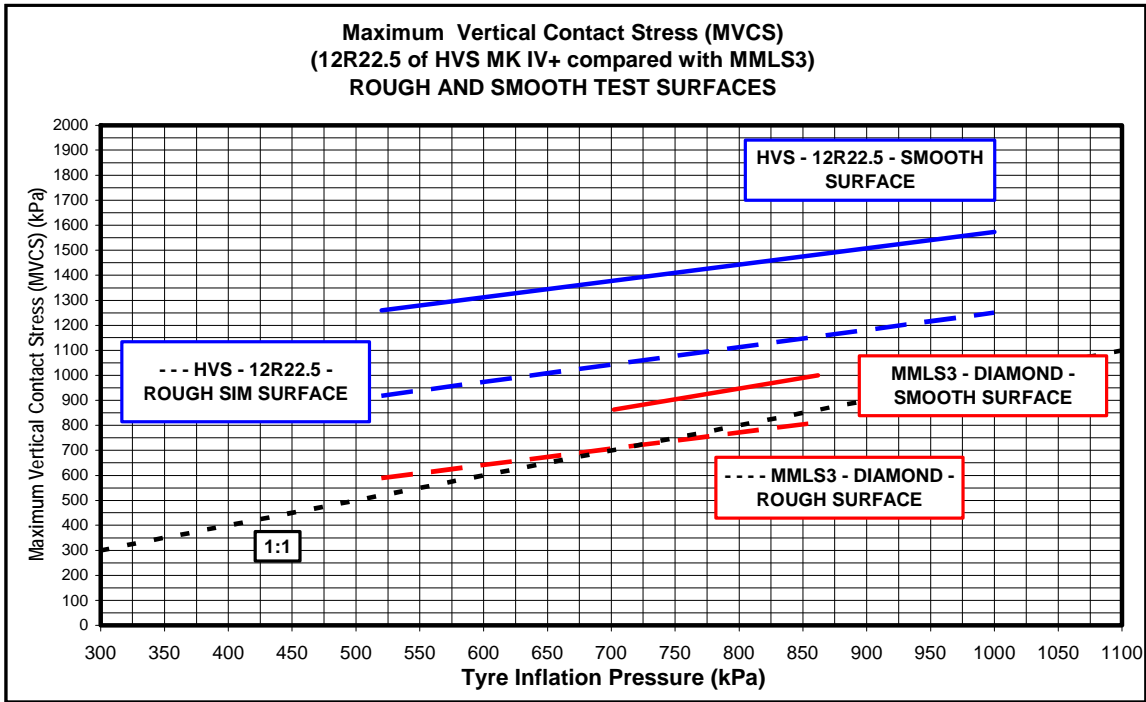


Figure 5. Average MVCS results for the HVS and the MMLS3 for both rough and smooth SIM test surface (this study).

4.2 Percentile results

For the purpose of this paper the summary data sets for all tested tyres in terms of percentile plots are illustrated in Figure 6, together with those of the MMLS3.

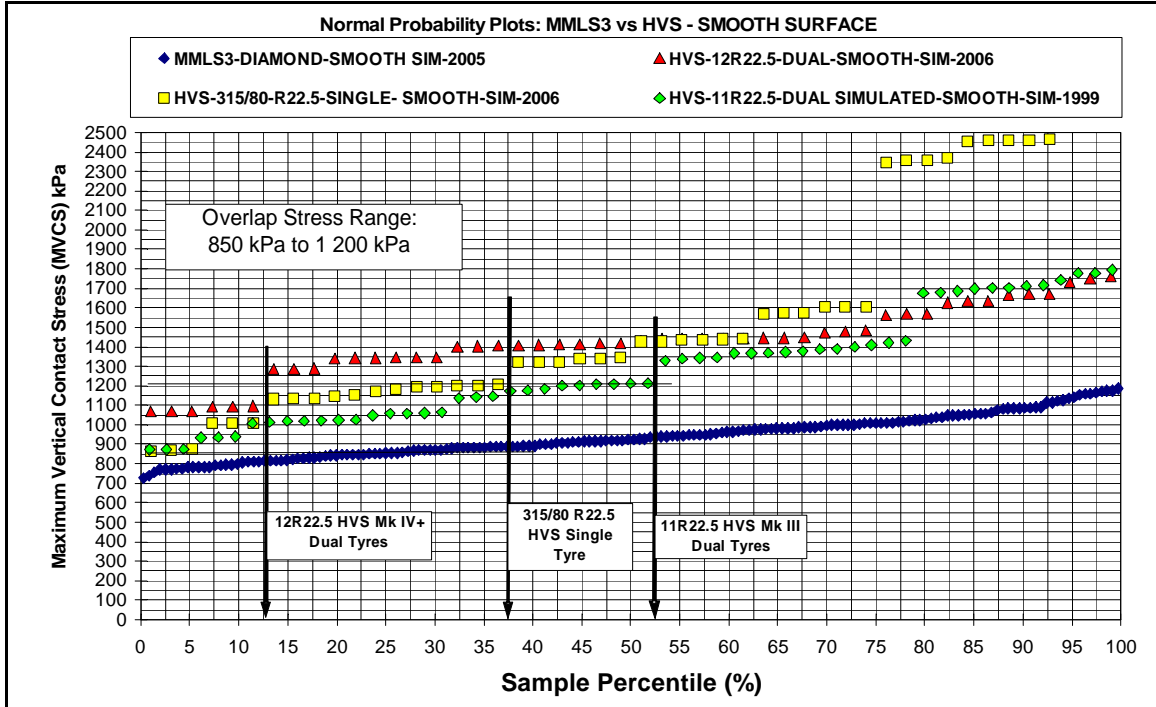


Figure 6, Per centile plots of the MVCS on the relatively smooth SIM surface for the MMLS3 Diamond tyres (S2 - this study) relative to three HVS test tyres.

Amongst others, the figure illustrates the following:

- Percentile plots of the MVCS results of the three HVS test tyres compared with the percentile plot of the MMLS3 D-tyre test – on the smooth test surface;
- The representative percentile of the 1/3rd scale MMLS3 D-tyre, compared with the 12R22.5 HVS full-scale tyre is approximately 12.5 per cent (P12.5) – (20 per cent on the rough-textured surface);
- The representative percentile of the 1/3rd scale MMLS3 D-tyre, compared with the 315/80 R22.5 HVS full-scale tyre is approximately 37.5 per cent (P37.5) – (similar on rough-textured surface);
- The representative percentile of the 1/3rd scale MMLS3 D-tyre, compared with the 11R22.5 HVS full-scale tyre is approximately 52.5 per cent (P52.5) – (similar on rough-texture);
- The MVCS range for HVS test tyres is approximately 850 kPa to 1 800 kPa on the smooth surface, and 700 kPa to 1 450 kPa on the rough-textured surface (for the test conditions used in this study, excluding the relatively high stresses for the 315/80 R22.5 tyre); and
- The MVCS range for MMLS3 test D-tyre is approximately 850 kPa to 1 200 kPa on the smooth surface, and 450 kPa to 1 000 kPa on the rough-textured surface (for the test conditions used in this study).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study describes the speed, loading and Maximum Vertical Contact Stresses (MVCSs) measured with the Stress-In-Motion (SIM) device for the different test tyres on the MMLS3 and the three full-scale test tyres used on the Heavy Vehicle Simulator (HVS). It was found that there were relatively large variations in speed and tyre loading between the different 1/3rd scale test tyres of the MMLS3, which were reduced when the speed referencing system of the SIM device was changed to a “rigid” system. However, under-recording of the MMLS3 loading was still observed for all three MMLS3 loading levels during the second series of testing (S2). It was found that the MVCS increased linearly with increasing tyre inflation pressure for both 1/3rd scale and full-scale test tyres. For the scaled-down tyres the MVCS was roughly equal to inflation pressure, whereas for the full-scale HVS tyres the MVCS was approximately 50 per cent higher. It was also found that the average MVCS (and vertical loading) for both the 1/3rd scale MMLS3 D-tyres and the three full scale HVS test tyres investigated here increased by 25 to 30 per cent when changing from a relatively rough-textured test surface to a relatively smooth test surface on the SIM device.

5.2 Recommendations

It is strongly recommended that the current MVCS results from this study be used for comparative purposes for *a more rational interpretation* of test data until further research proves otherwise. It is also recommended that further studies on different test surfaces be addressed in future research. It is however, critically important that loading devices such as the HVS and MMLS3 be adequately calibrated before similar studies are done in the future. The anchoring of the MMLS3 to the road pavement is also specifically important here.

6. ACKNOWLEDGEMENTS

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