Paper Title:

Towards Quantifying Horizontal Stresses of Free-Rolling Pneumatic Rubber Tyres on Road Surfacings

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CSIR Built Environment
Pretoria and
E M SADZIK (former Gautrans)

our future through science

Project Background:

- Tyre Study Project initiated by Gauteng Department of Public Transport, Roads and Works (GDPTRW);
- Accelerated Pavement Testing (APT) Strategy of 2004;
- Heavy Vehicle Simulator (HVS), and
- 1/3rd Scale Model Mobile Load Simulator (MMLS3), using
- Locally developed Stress-In-Motion (SIM) device

Project Objectives:

- Quantification of the 3D tyre-pavement contact stresses of the HVS and MMLS3 test tyres (using Stress-In-Motion (SIM) device);
- Results of 5 x Tyres in this paper;
- Focus mainly on the Horizontal (tangential) Stresses (X,Y) in this paper;
- In corporation into Mechanistic – Empirical Design ?
- Conclusions and Recommendations.

”Sectometer”
S. Eckens, 1928

Modern Tyre science…

The "sectometer" was leveled (Figure 4), and the height of the springs were measured with nine inch micrometer calipers (Figure 1). The

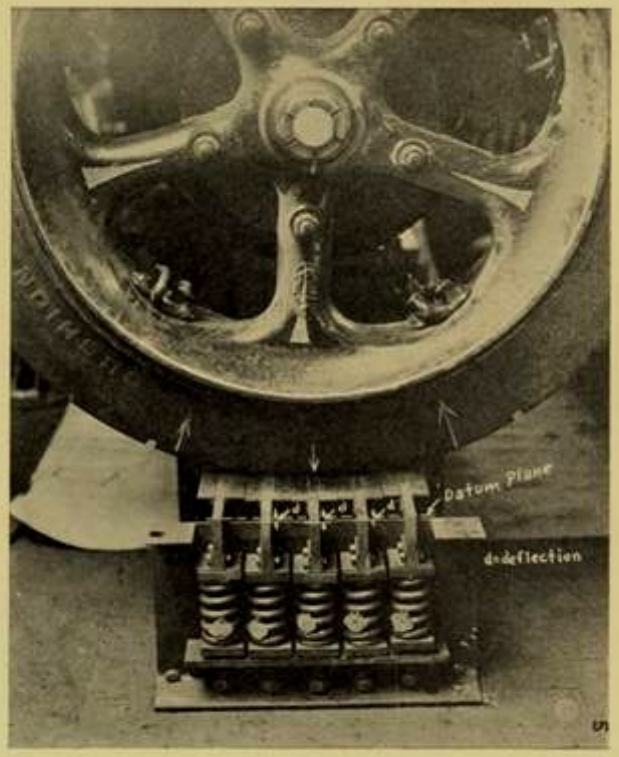
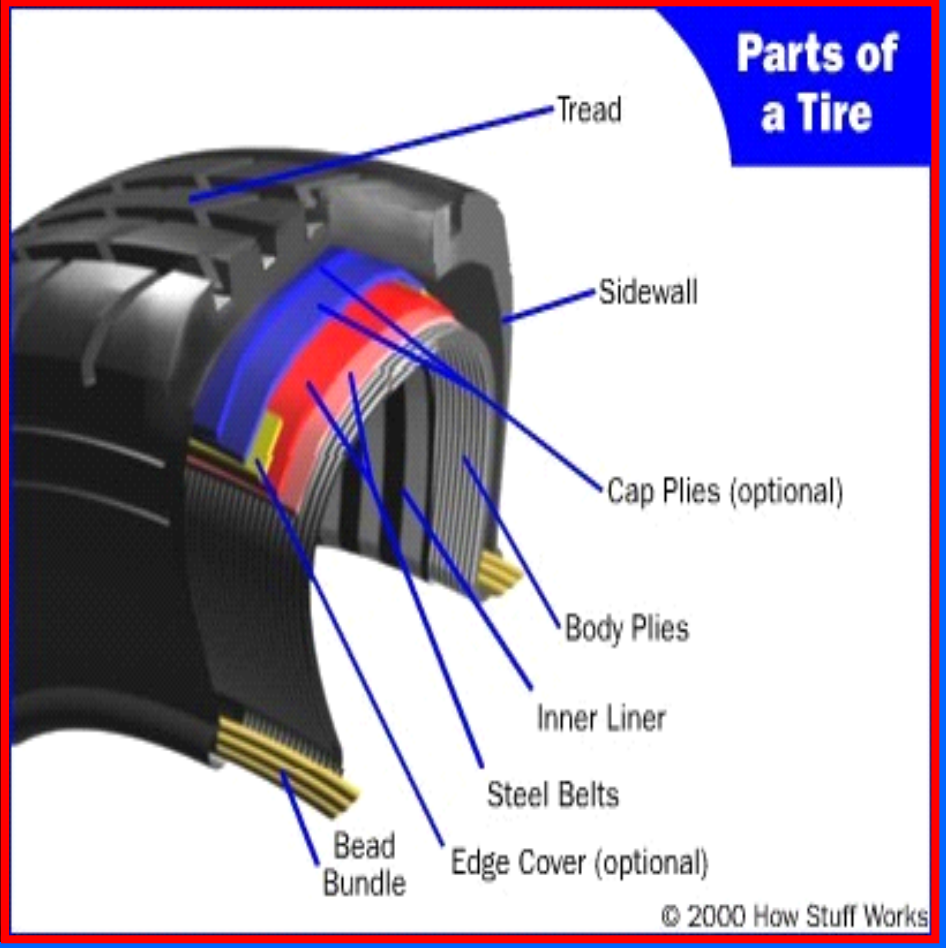
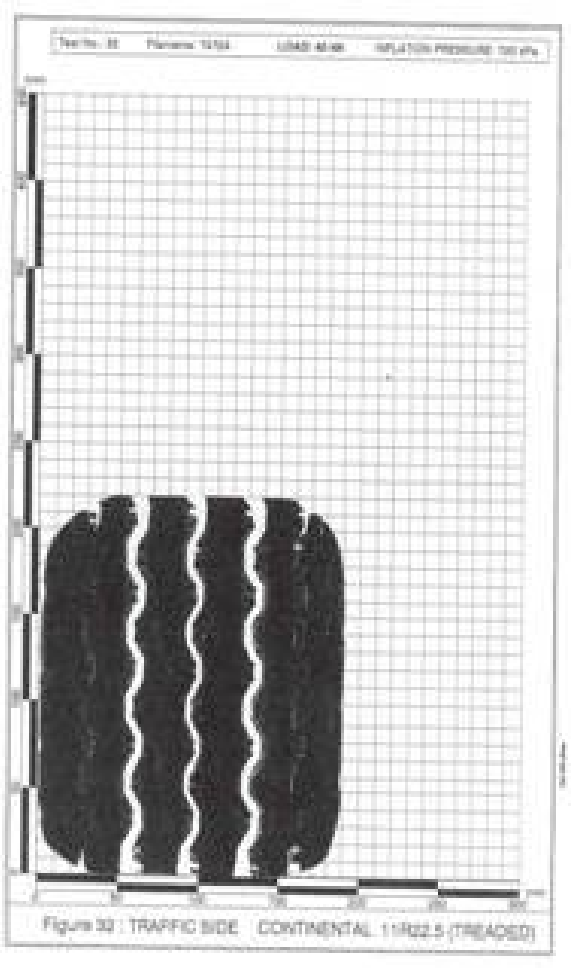


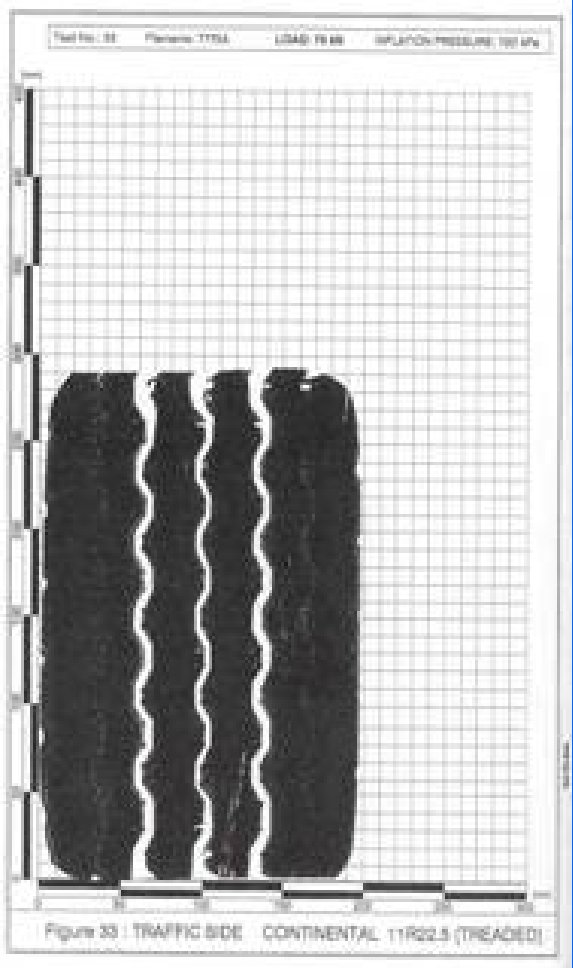
Figure 5

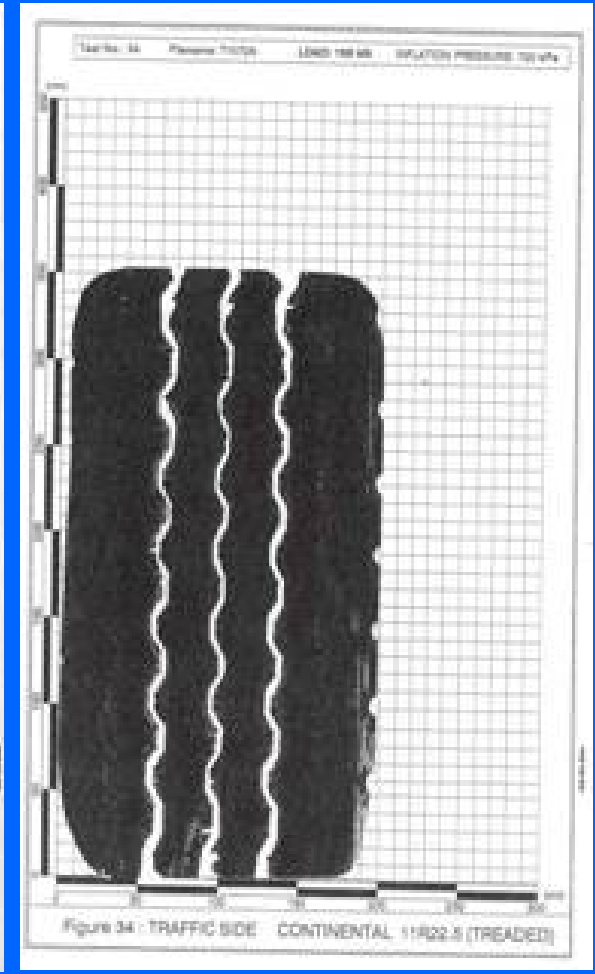
machine was now in position for the impression and also for the determination of the load distribution.



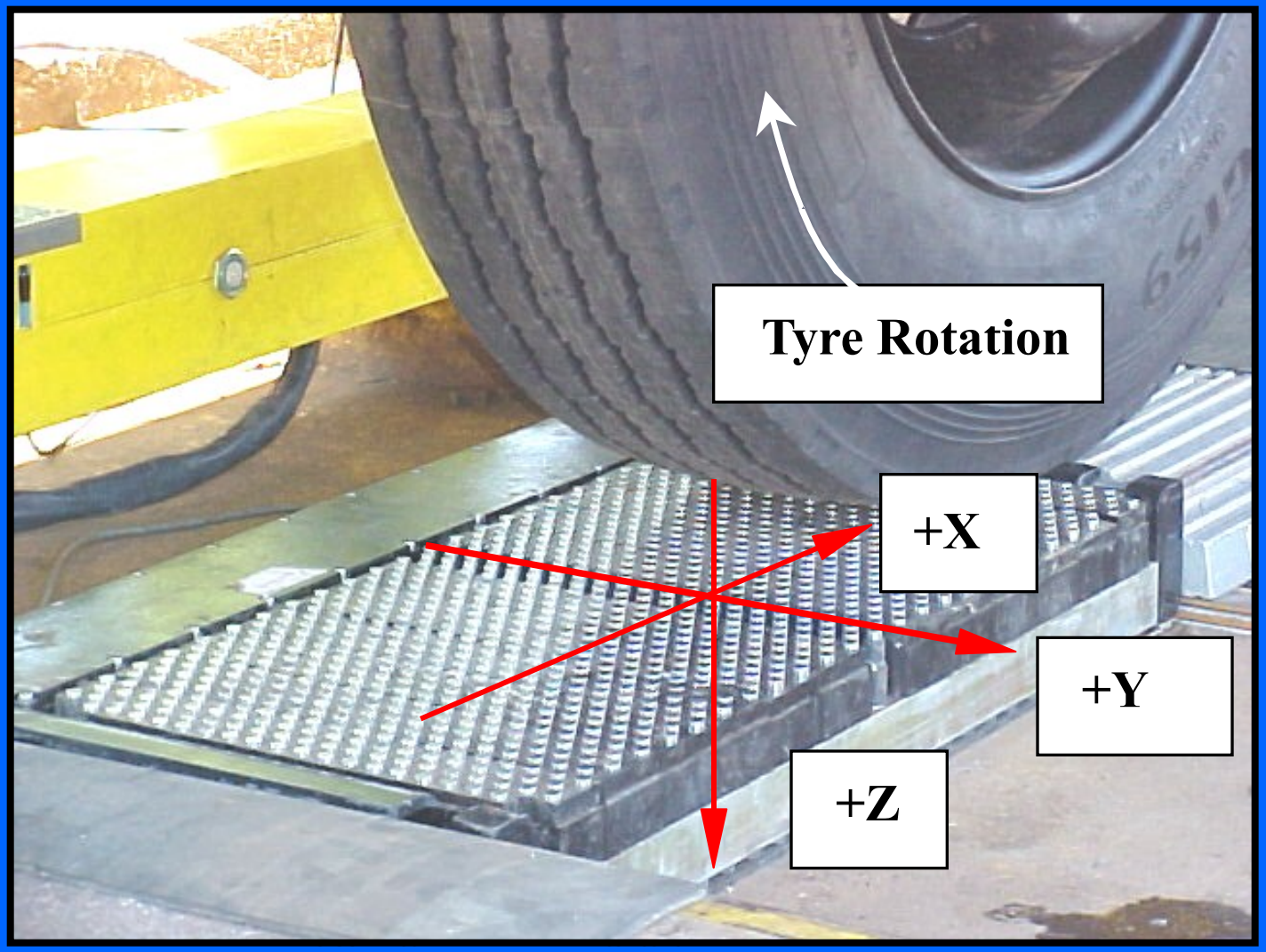
Tyre Prints @ different loadings… 11R22.5 HVS test tyres







Sign convention: SIM measurements. X-Longitudinal, Y-Lateral and Z -Vertical loads/stresses.

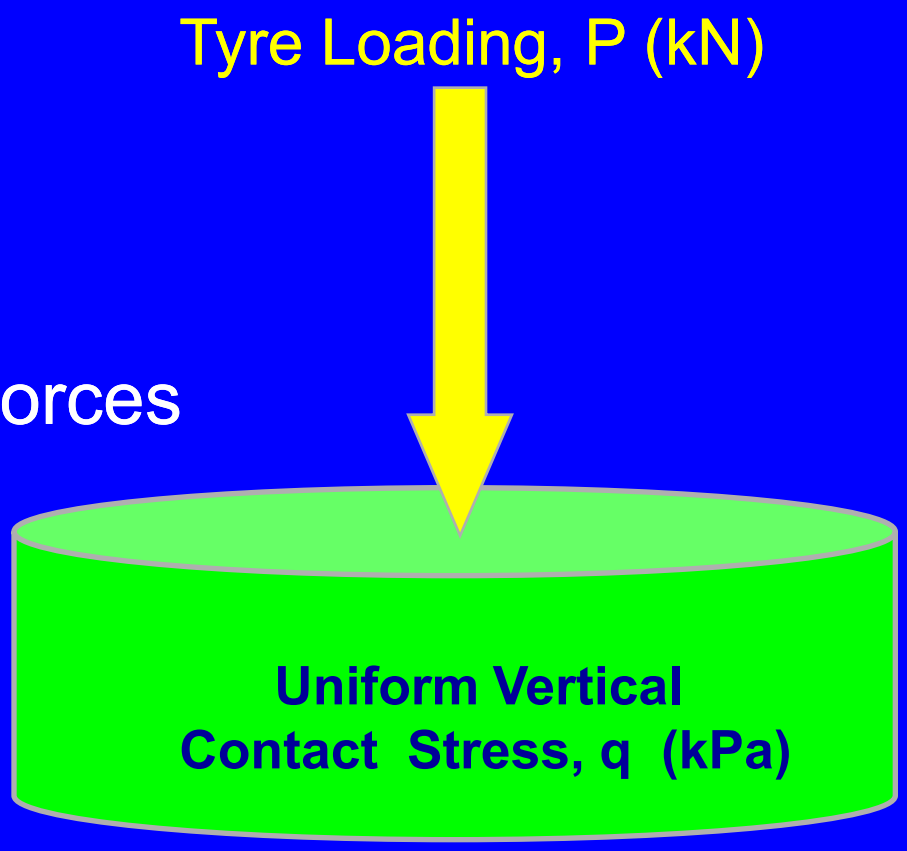


Assumption of Tyre Loading - Pavement Design Modeling:

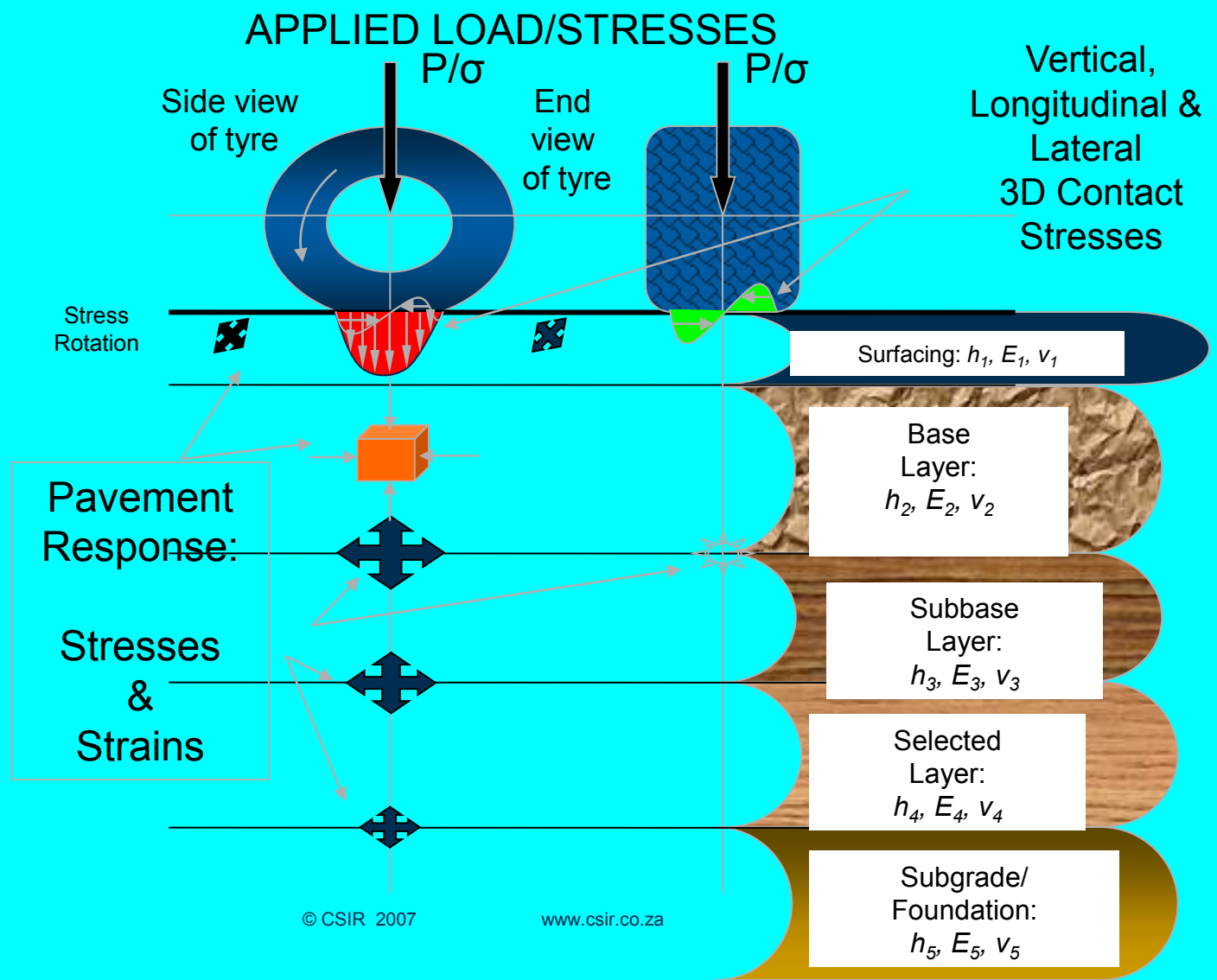
- Circular;
- Variable Vertical load;
- Variable pressure,

but UNIFORM &

No Shear (tangential) Forces included yet...



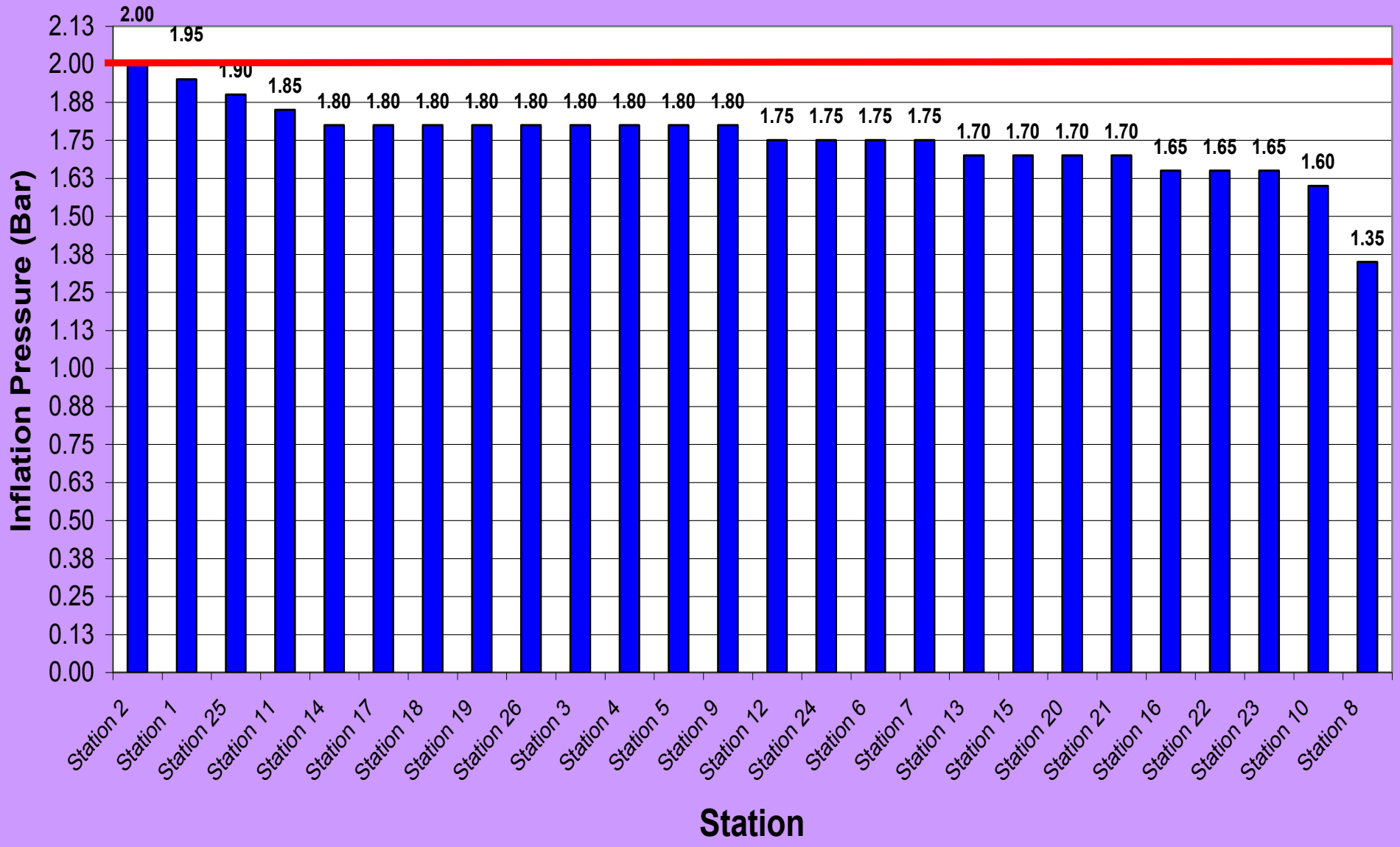
Road/Tyre Interaction and Mechanistic Design



Road Infrastructure:

Heavy Vehicles - Road Users:

Inflation Pressure check at Filling Stations - Pta (2008)
(Pta News - Thursday - July 3, 2008)

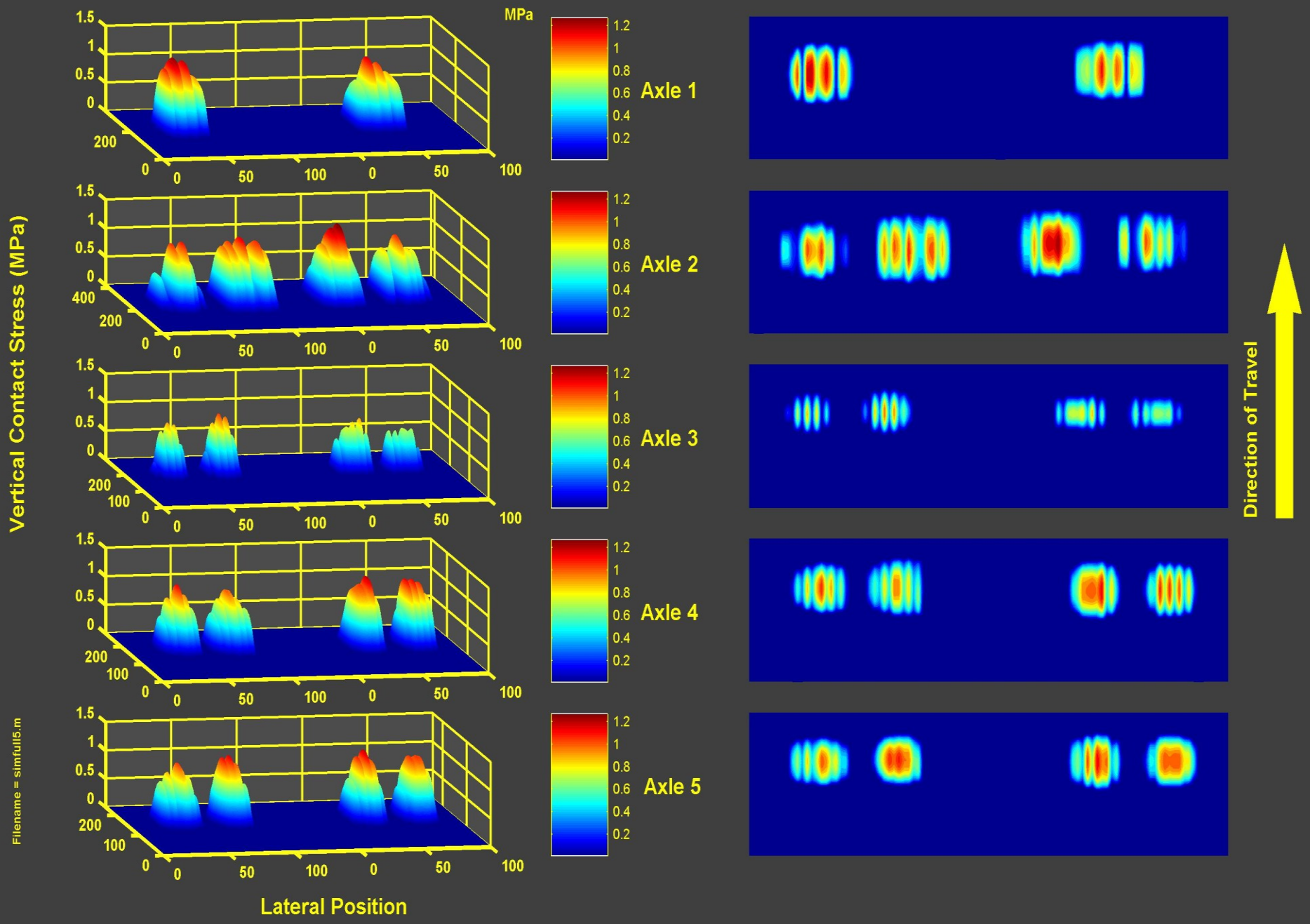


Road Failures:

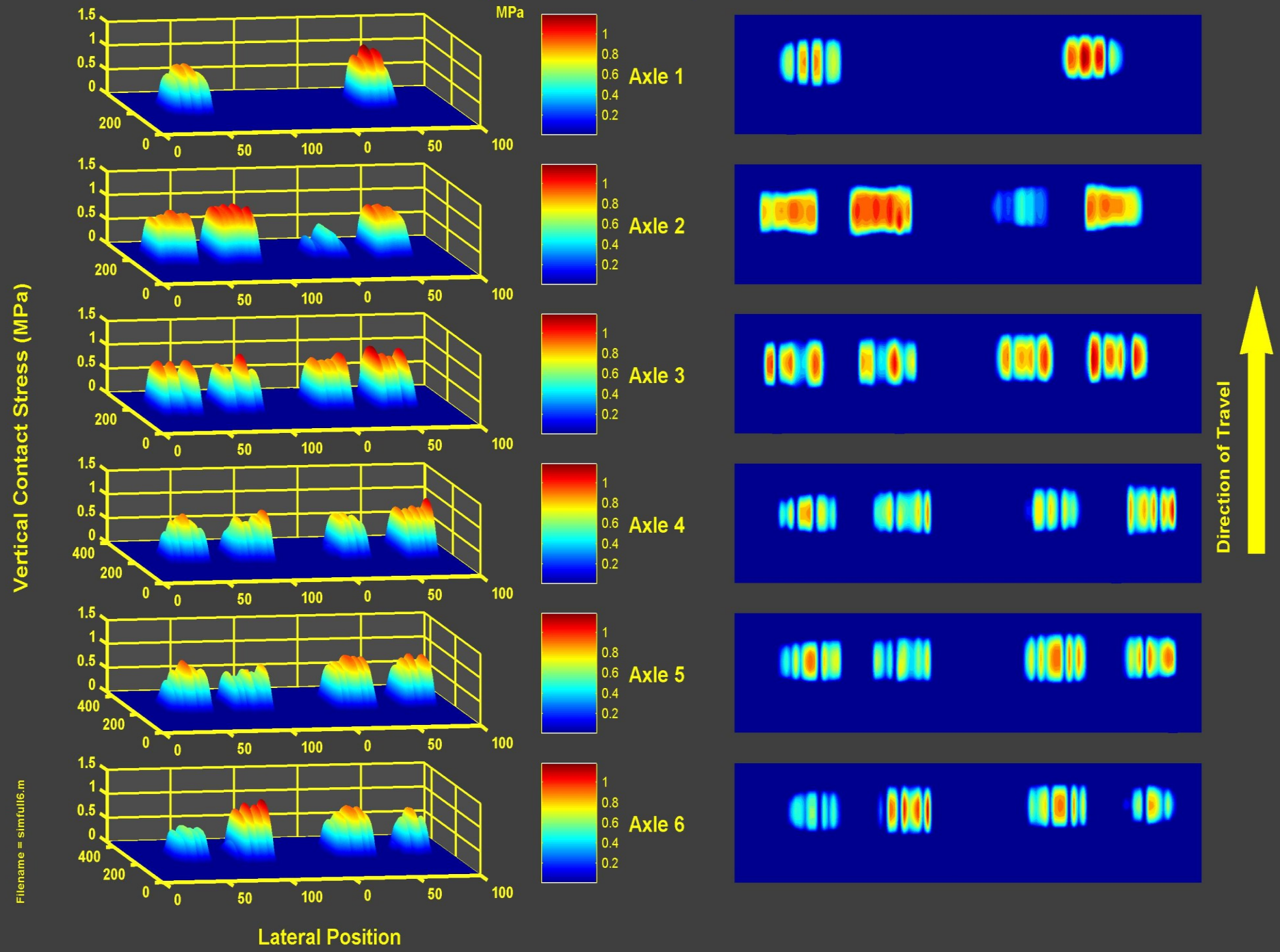
Quad (full) SIM pad configuration at the weighbridge site on National Road 3 (N3), near Heidelberg in Gauteng (2003)

STRESS-IN-MOTION (SIM) TESTING ON N3 - FREEWAY

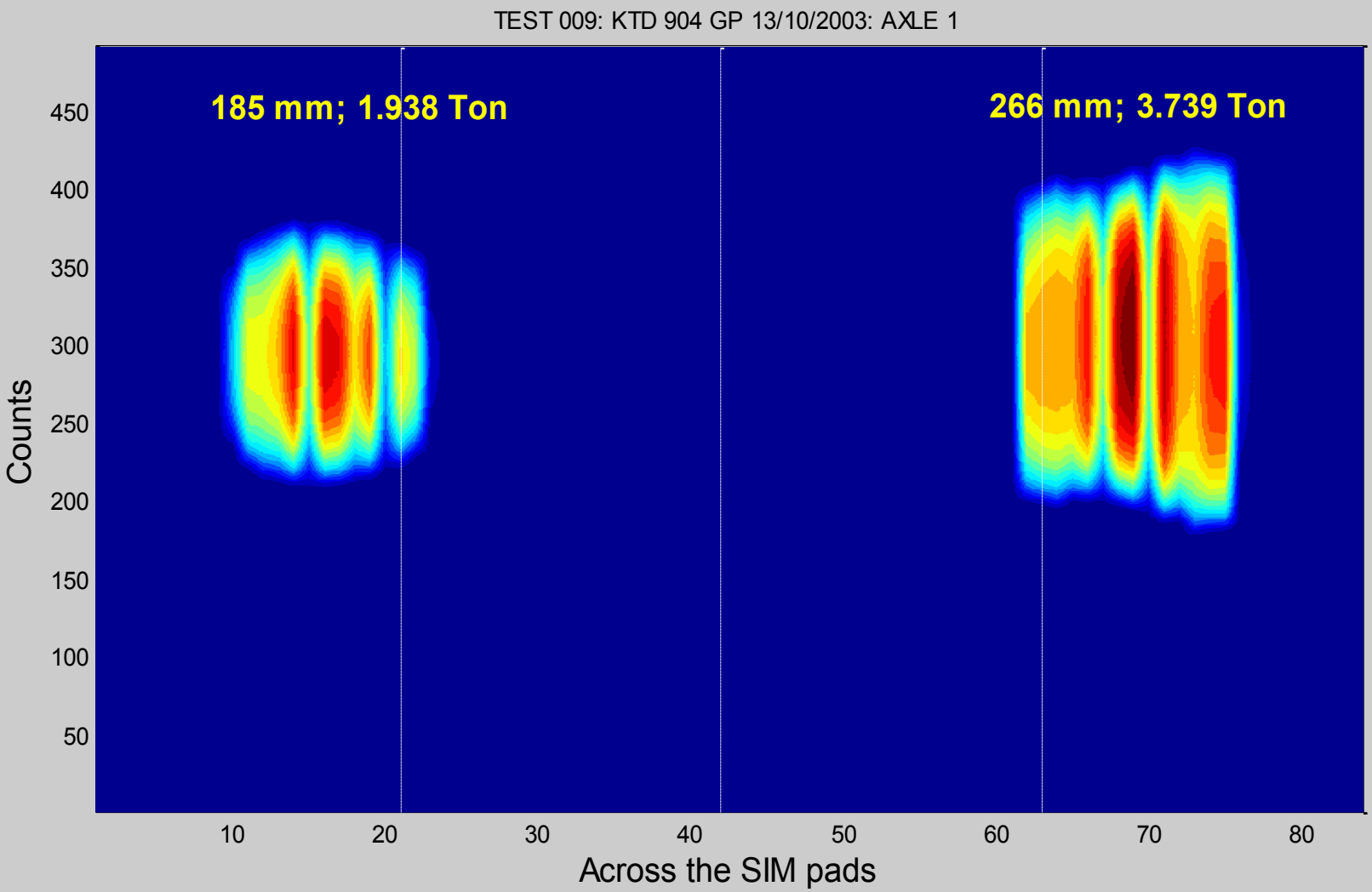
Test H1077 done at Heidelberg : Date 10/09/2003



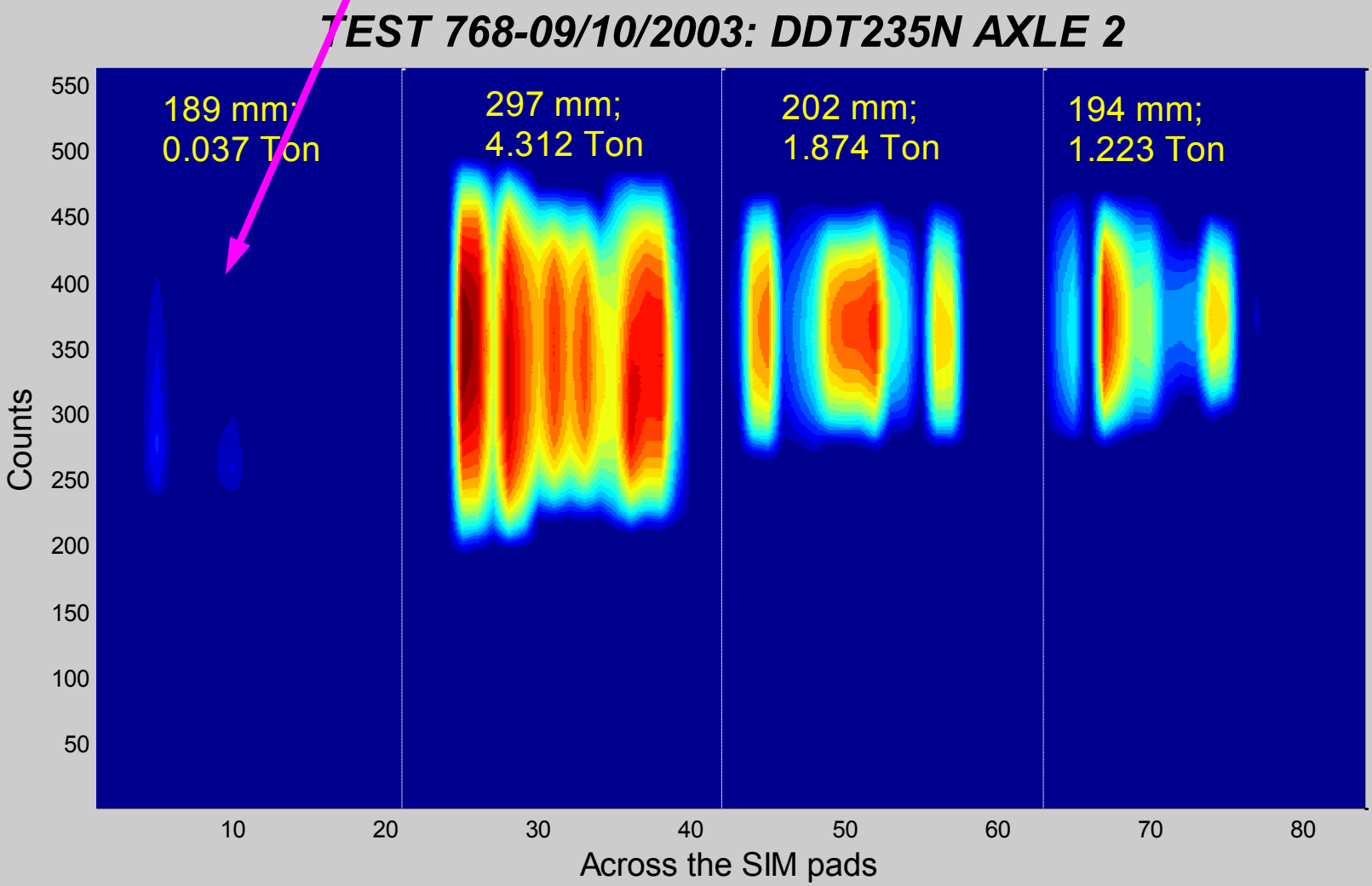
Test 174 done at Heidelberg : Date 10/09/2003 (overload)



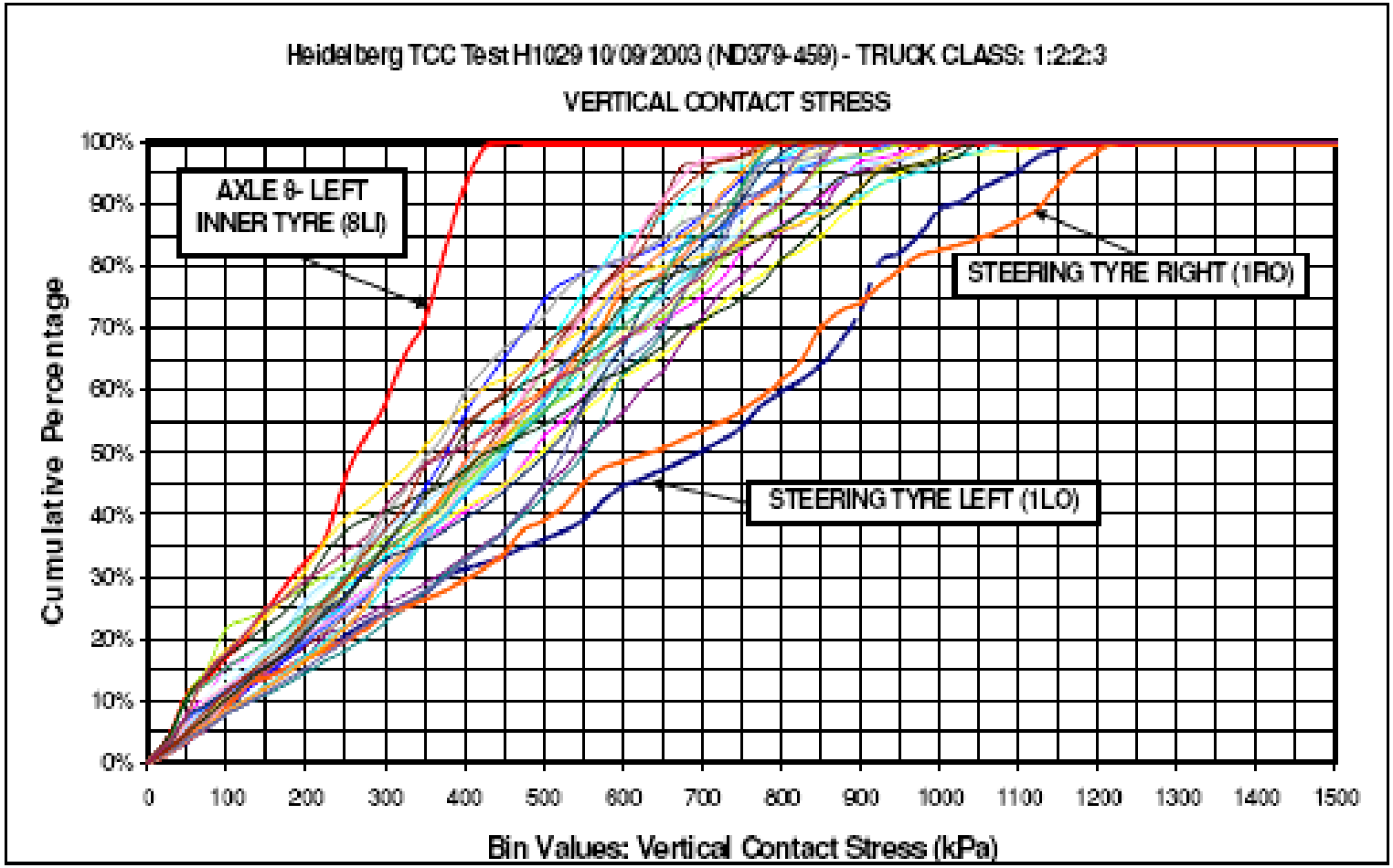
STEERING AXLE – UNEQUAL LOADING



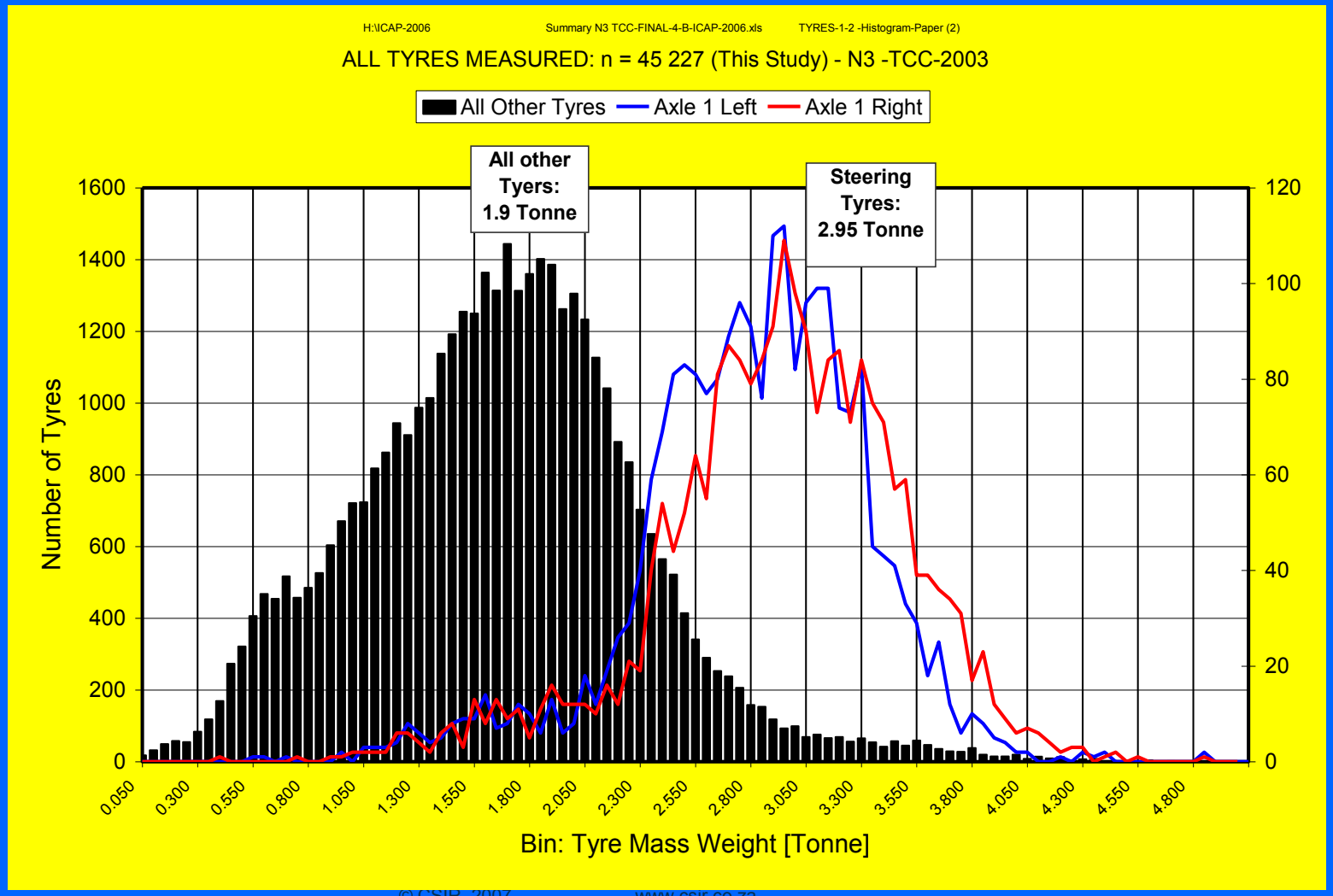
TYRE BARELY IN CONTACT WITH SURFACE



Example of variation in vertical contact stress of a real truck….



Axle Mass Distributions – N3 – 2003 Study



Heavy Vehicle Simulator (HVS) of Gautrans (GDPTRW) – Full Scale

Tyres and surfaces tested:

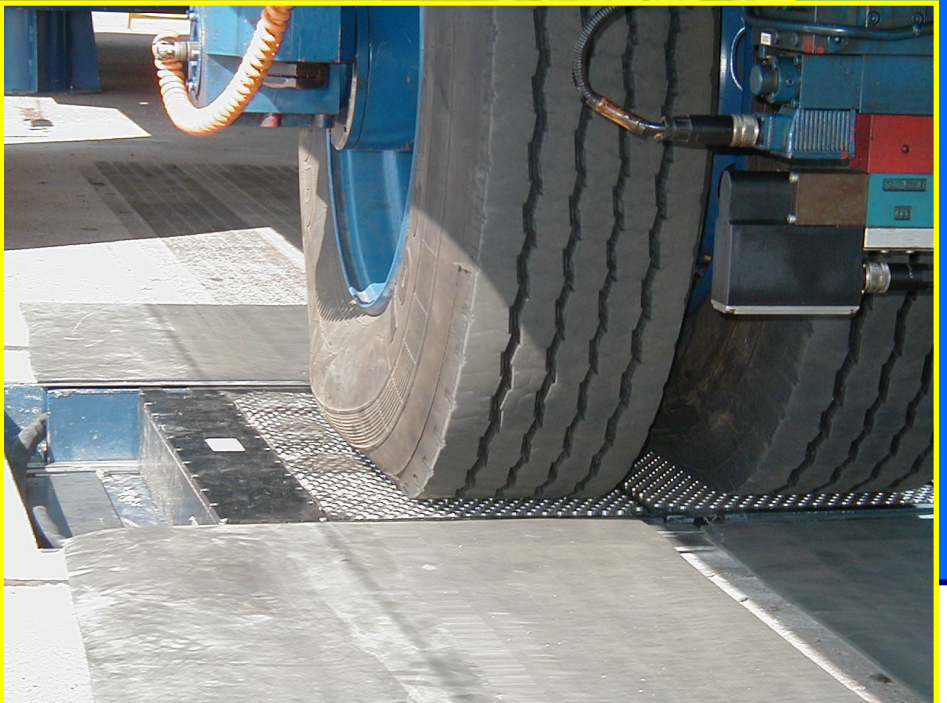
- Single wide base 425/65 R22.5 tyre (on Rough-Textured (RT) surface);
- Single 315/80 R22.5 full-scale tyre (on RT and Smooth (S) surfaces);
- Dual 12R22.5 full-scale tyres (on RT and S surfaces);
- Dual 11R22.5 full-scale tyres (on RT surface), and
- a 1/3rd scale MMLS3 Diamond Tyre (D-tyre), with a square tyre profile – (on RT and S surfaces).

HVS Mk IV+ Full Scale Test Tyres

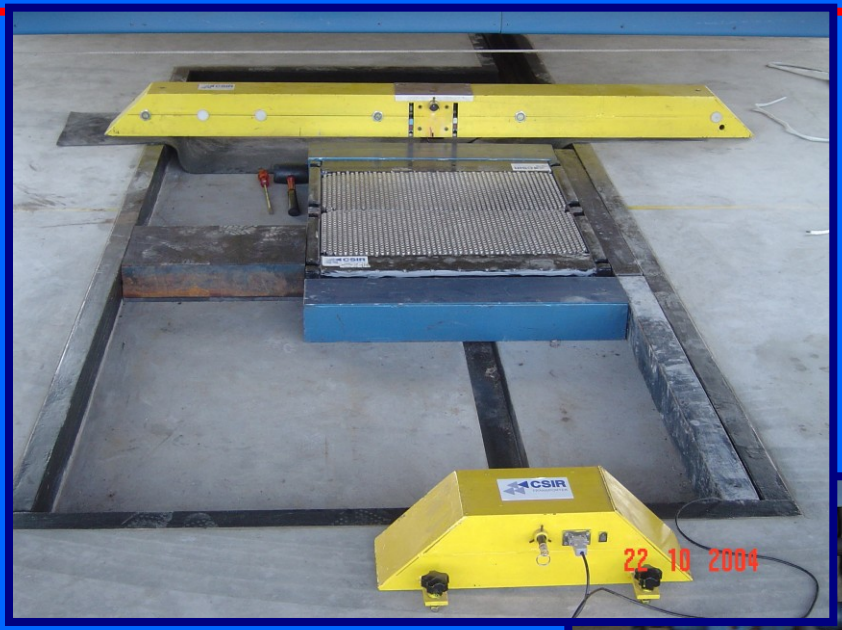
DUAL: 12R22.5
(Steering, driving and Trailing

SINGLE: 315/80 R22.5
(Also on steering Axle)

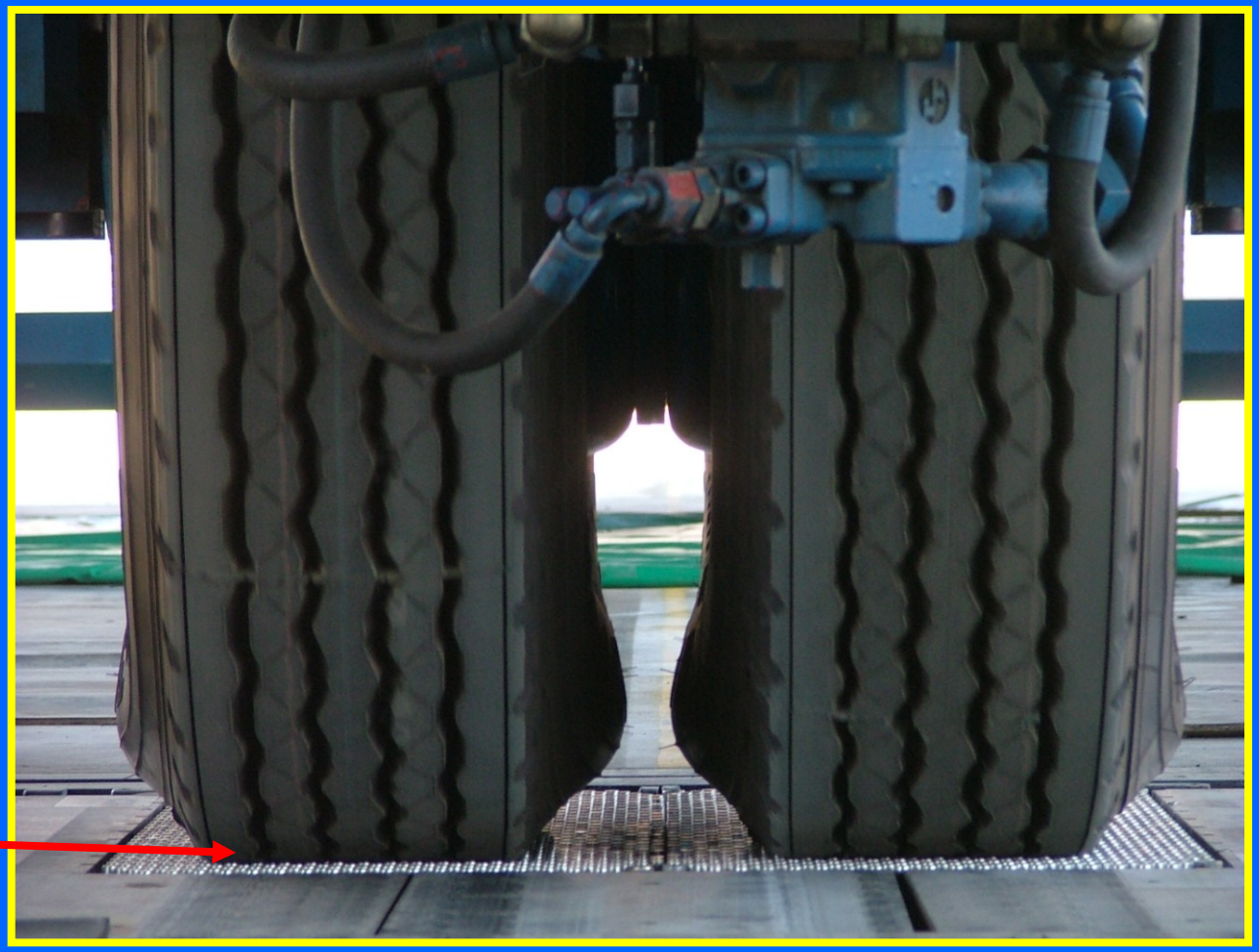
Oct 2004 - HVS –SIM TESTS



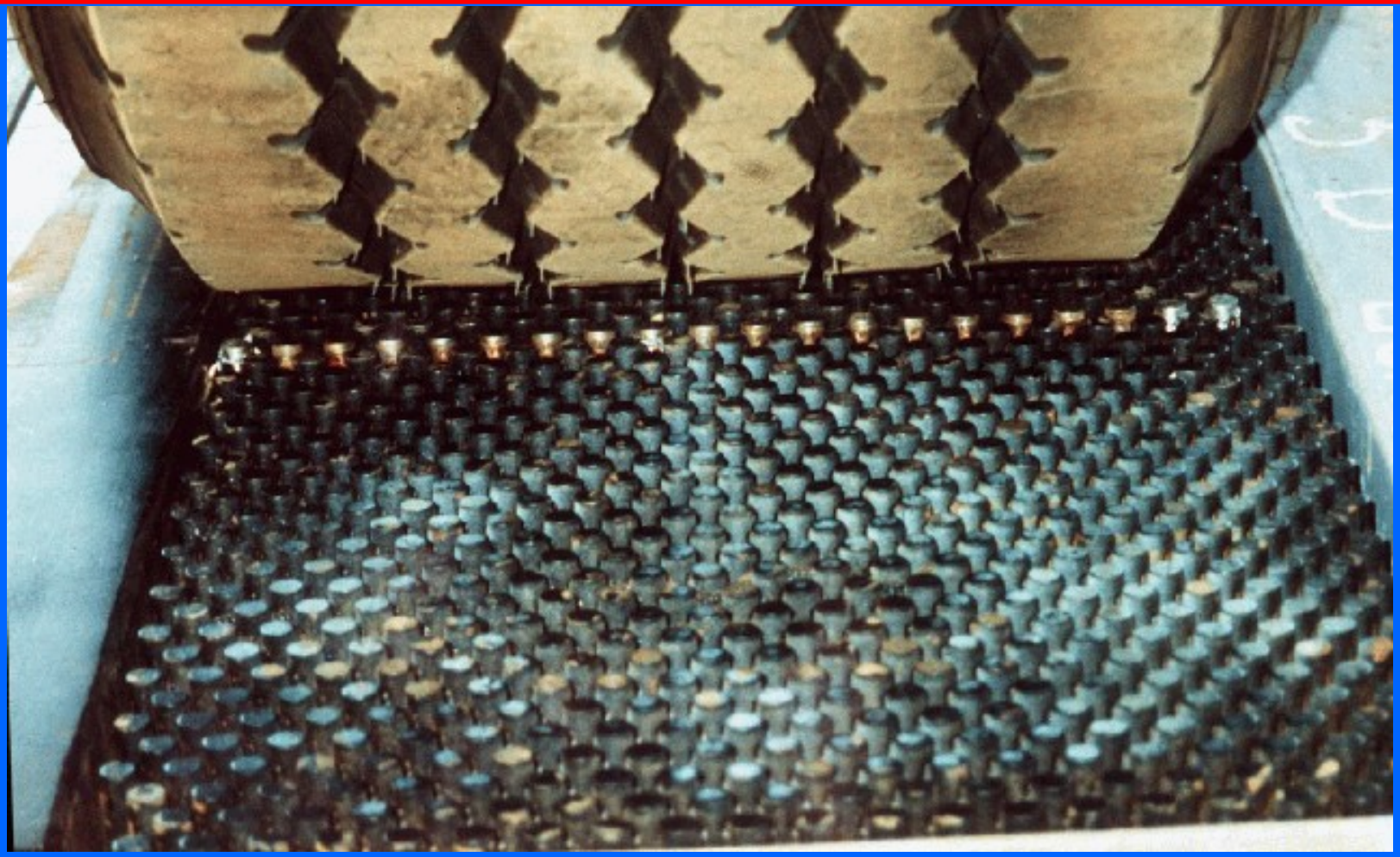
Dual SIM system during HVS tyre testing @ Gautrans Laboratory



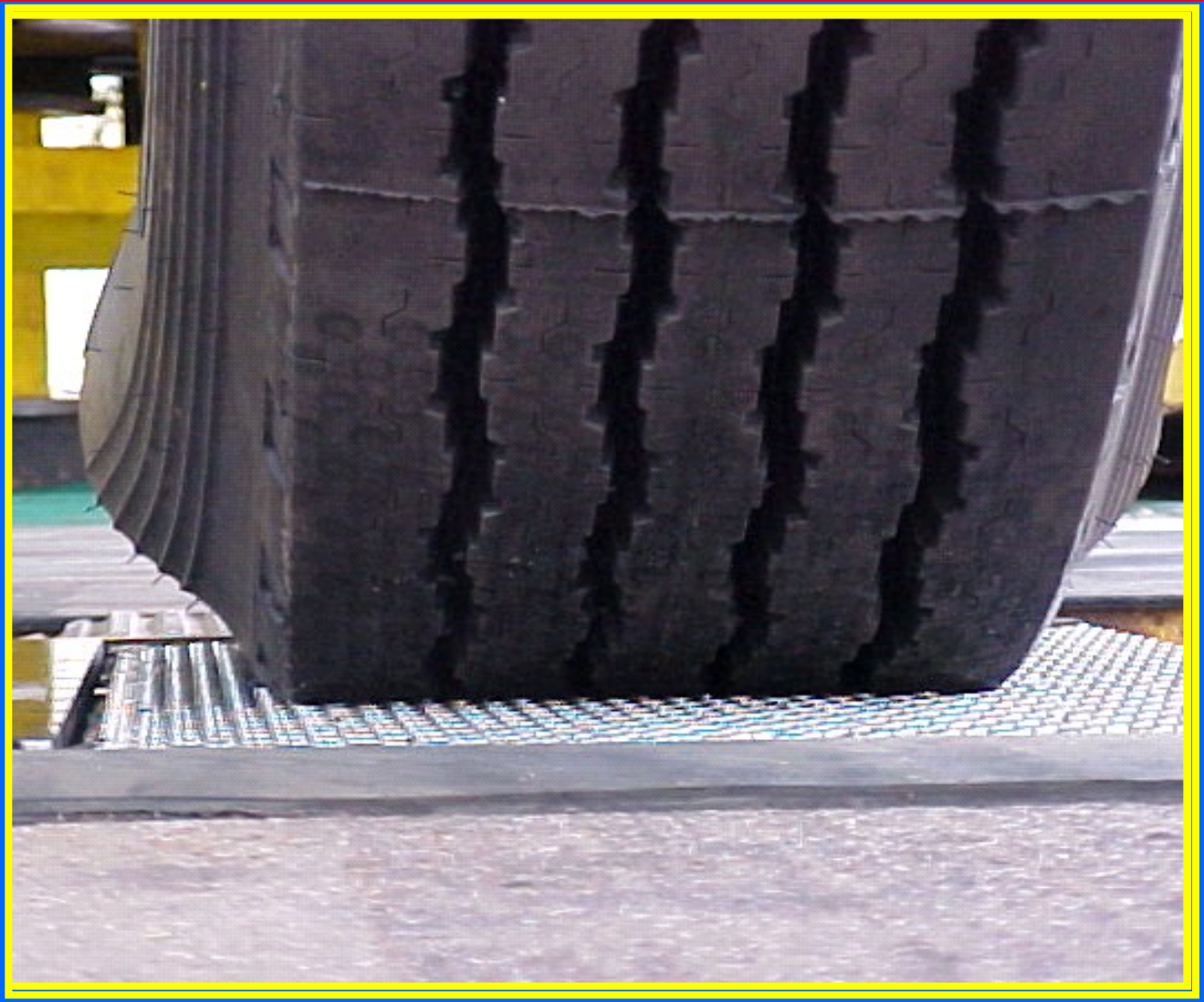
HEAVY VEHICLE SIMULATOR (HVS) DUAL TEST TYRES (12R22.5)



425 /65 R22.5 HVS TIRE ON SIM SYSTEM

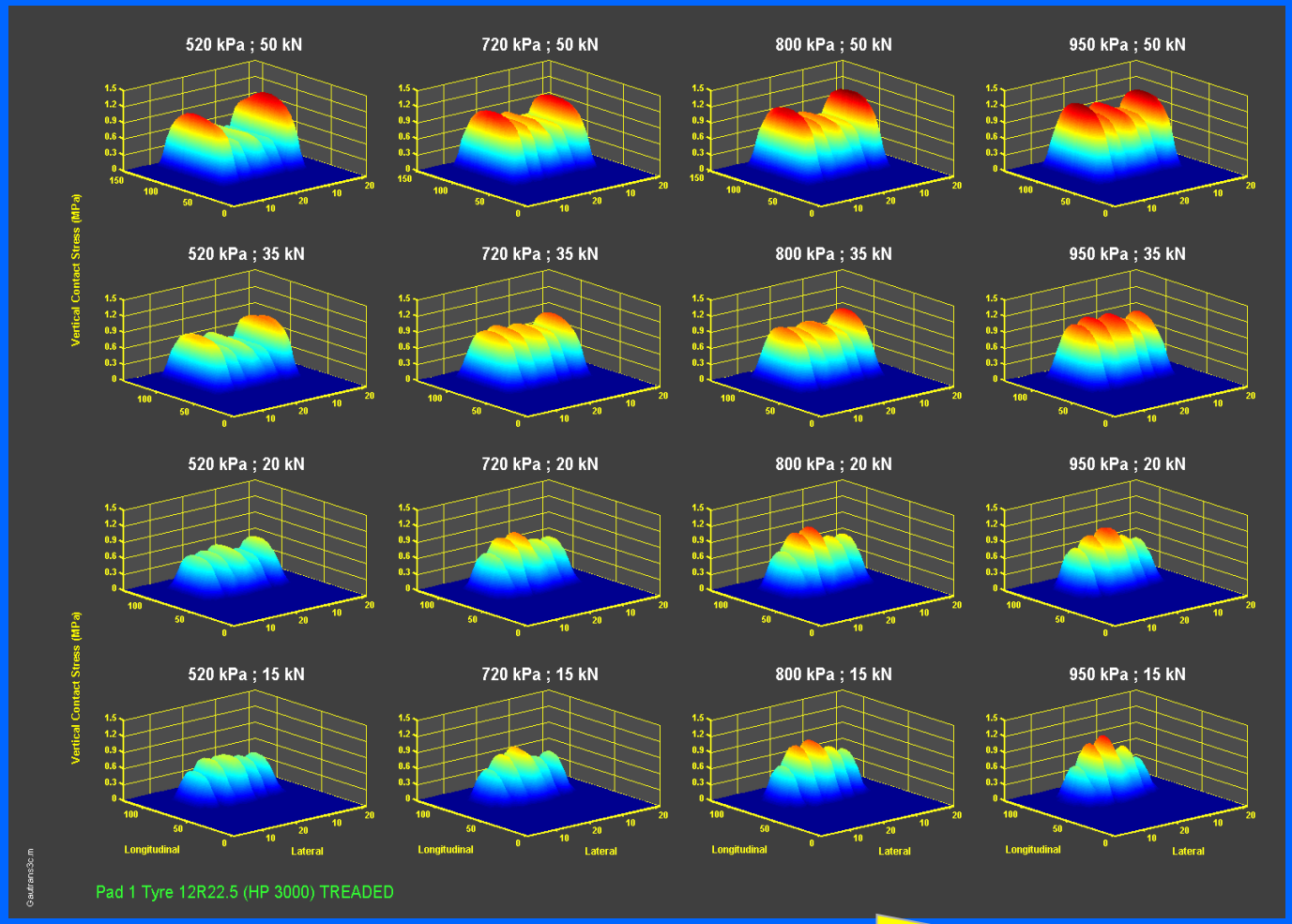


315/80 R22.5 HVS Tyre: Overloaded



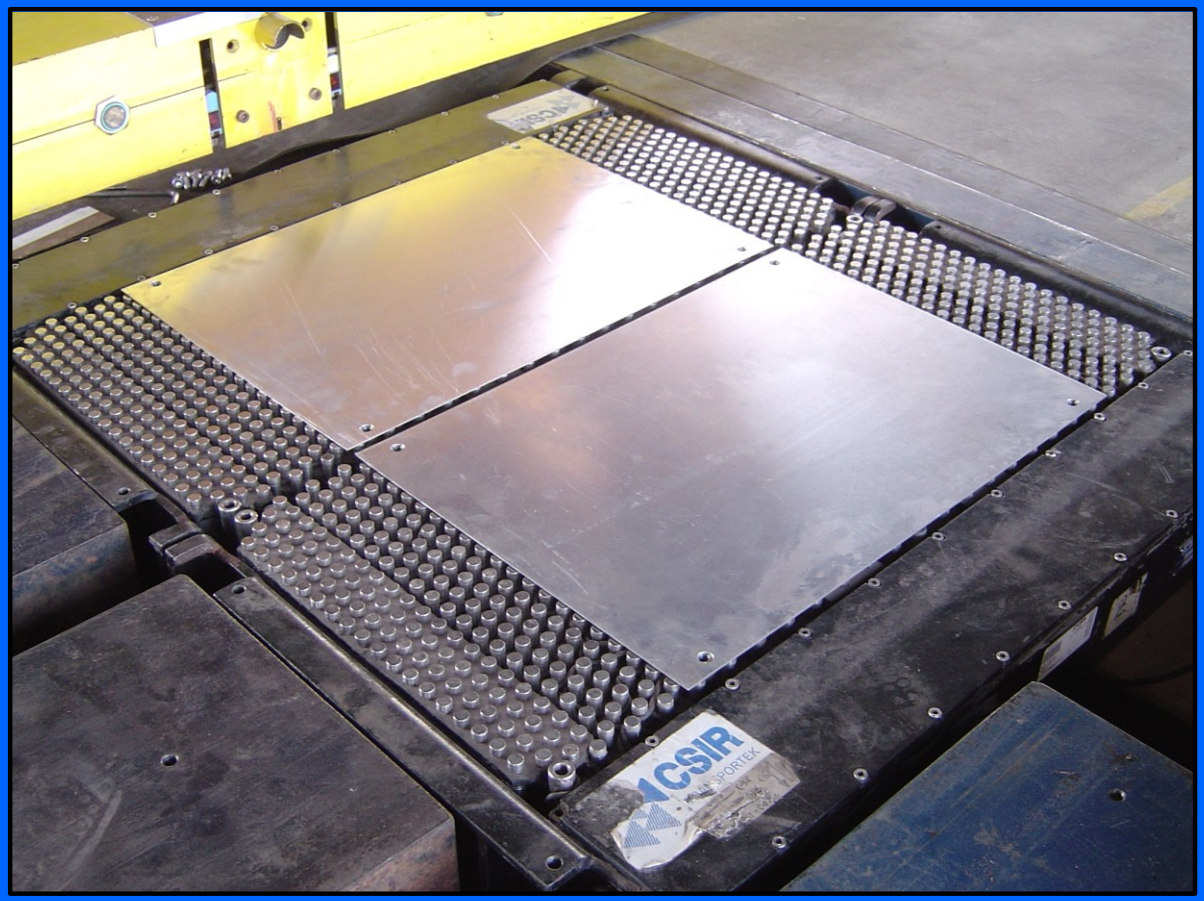
“FINGER PRINTING” - VERTICAL CONTACT STRESS (HVS 12R22.5)

TYRE LOAD



INFLATION PRESSURE

Smooth - 0.9 mm Aluminium Plates – HVS Dual Tyre Tests on SIM



Model Mobile Load Simulator (MMLS3) – 1/3rd Scale

MMLS3 Test Tyres (1/3rd Scale)

MMLS3 Test Tyres (1/3rd Scale) – on Rough-Textured Surface..

MMLS3 Test Tyres (1/3rd Scale)- on Smooth Plate..

MMLS3 on SIM: Creep Speed illustration of tyre interaction on artificial textured surface…

Relative Comparison

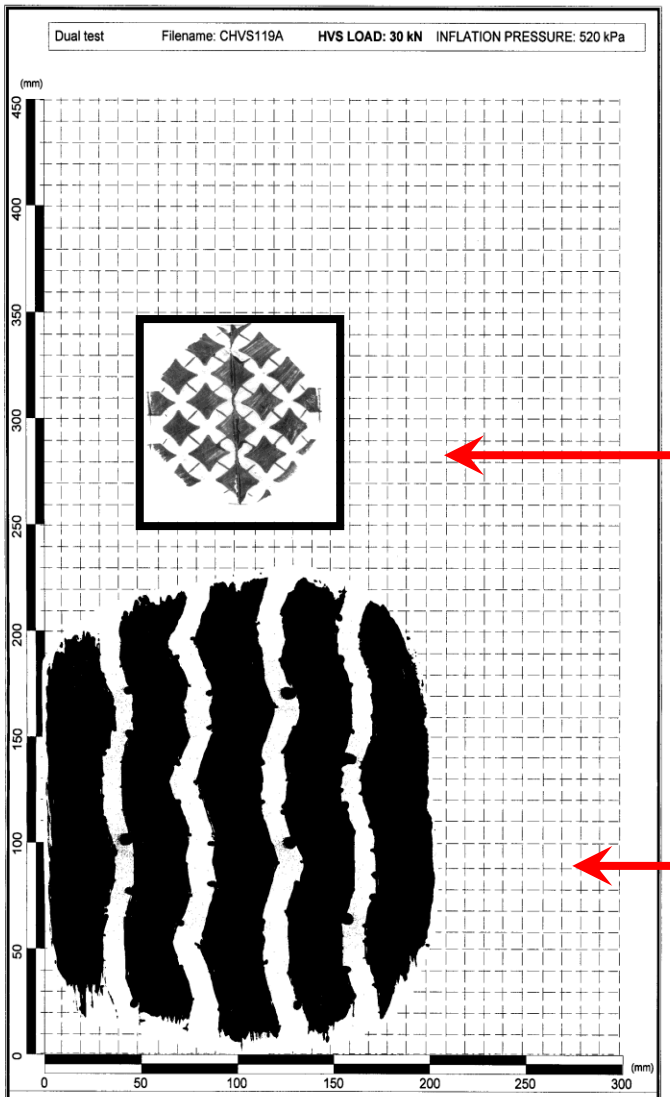
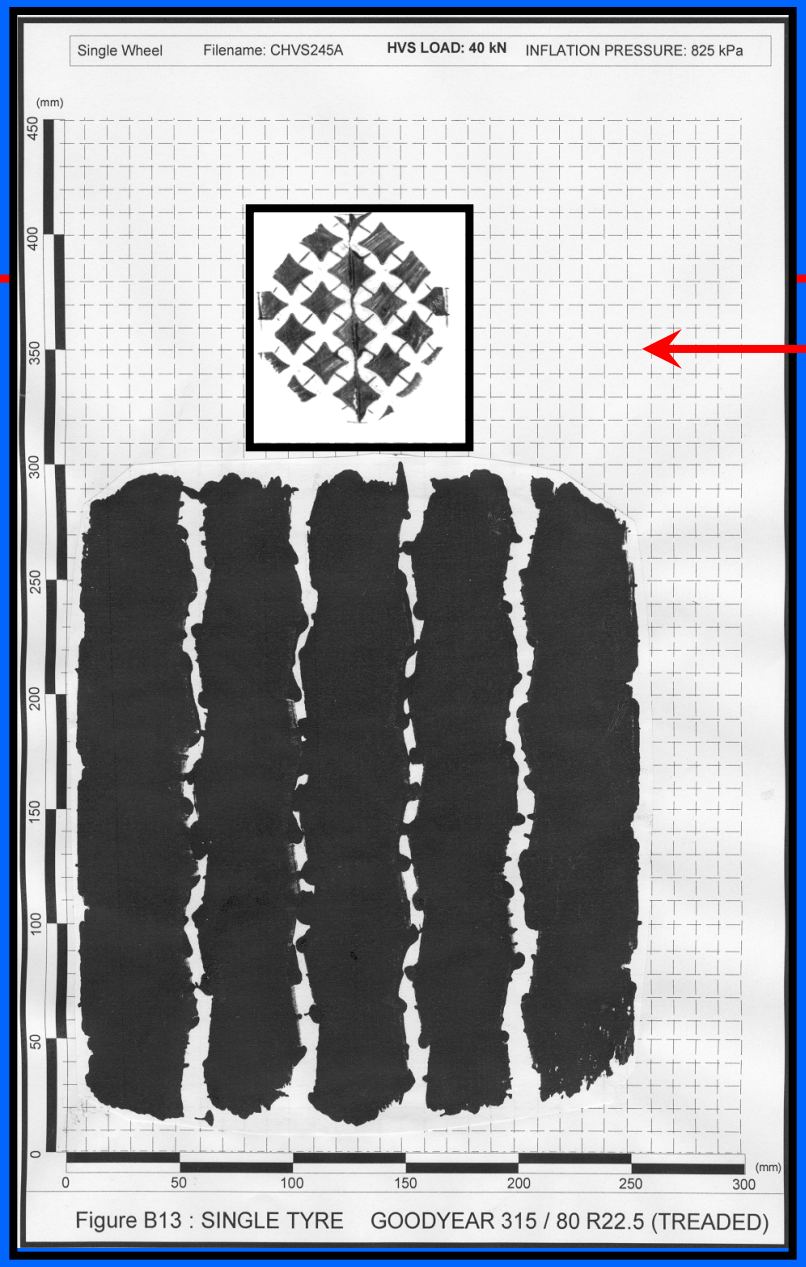


Figure B1 : CARAVAN SIDE FIRESTONE 12R12.5 (TREADED)

MMLS3-Square Profile
(2.9 kN @ 700 kPa)

HVS 12R22.5
(30 kN @ 520 kPa)

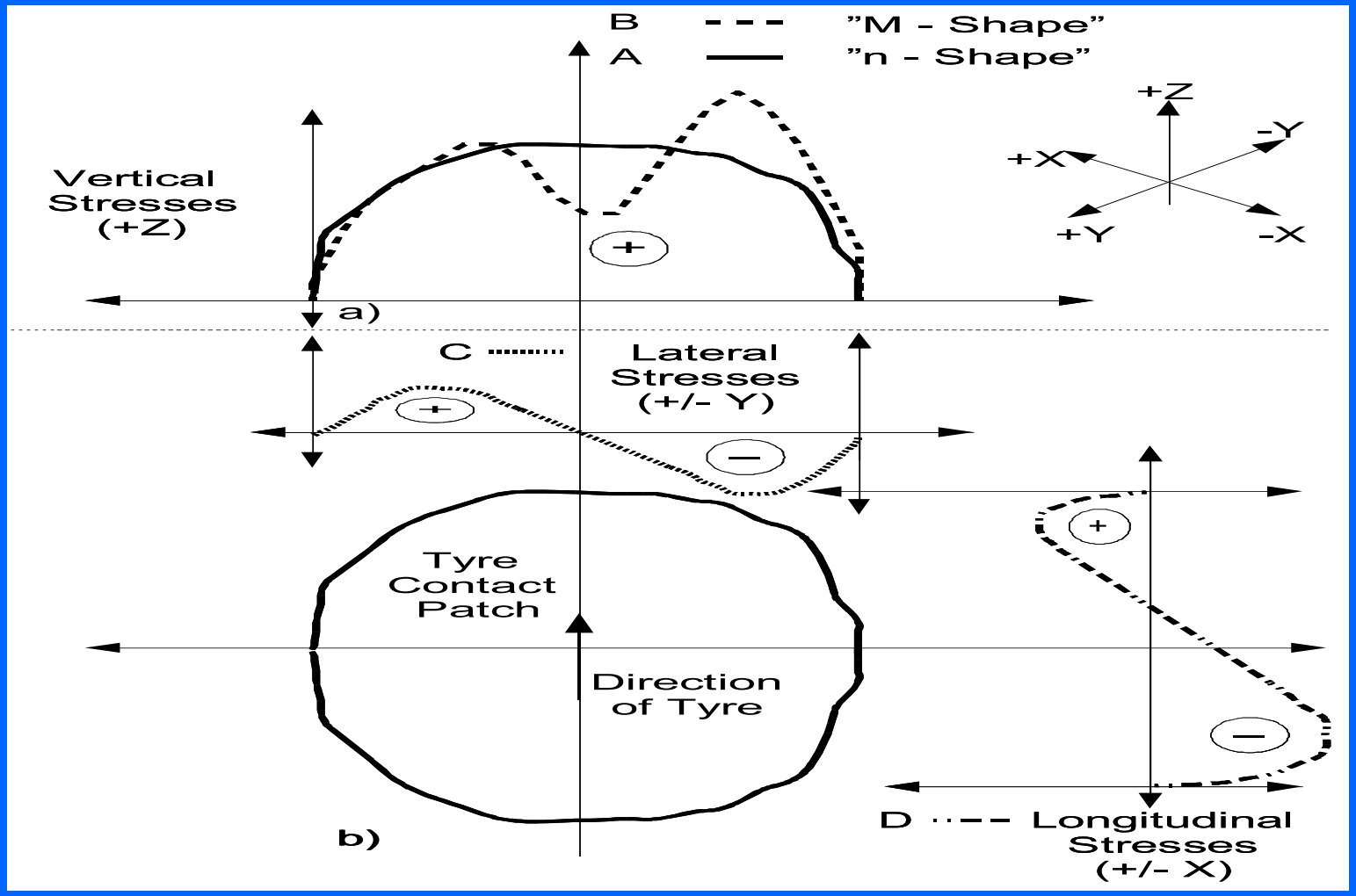
Steering Tyres



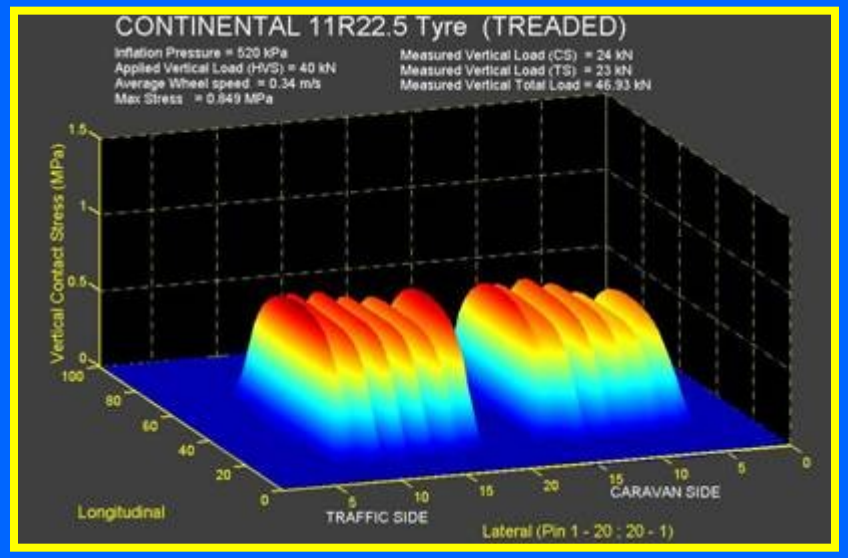
MMLS3-Square Profile (2.9 kN @ 700 kPa)

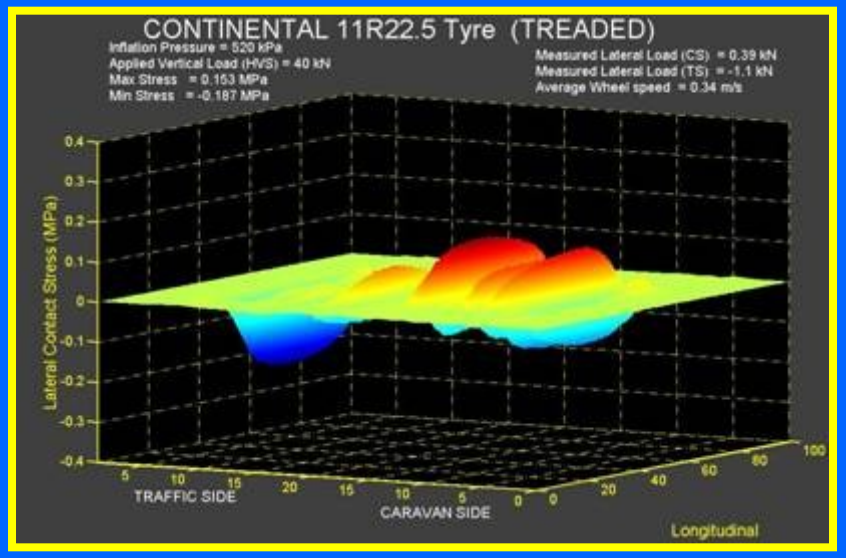
HVS 315/80 R22.5 (Steering Tyre – 40 kN @ 825 kPa))

Basic 3D Contact Stresses

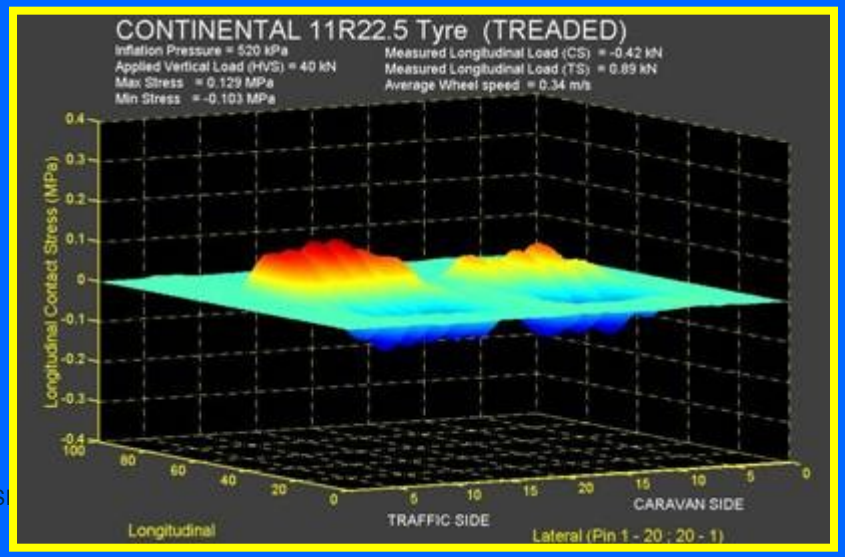


Dual Tyre: 3D-Road Contact Stresses- 80 kN Standard Axle….

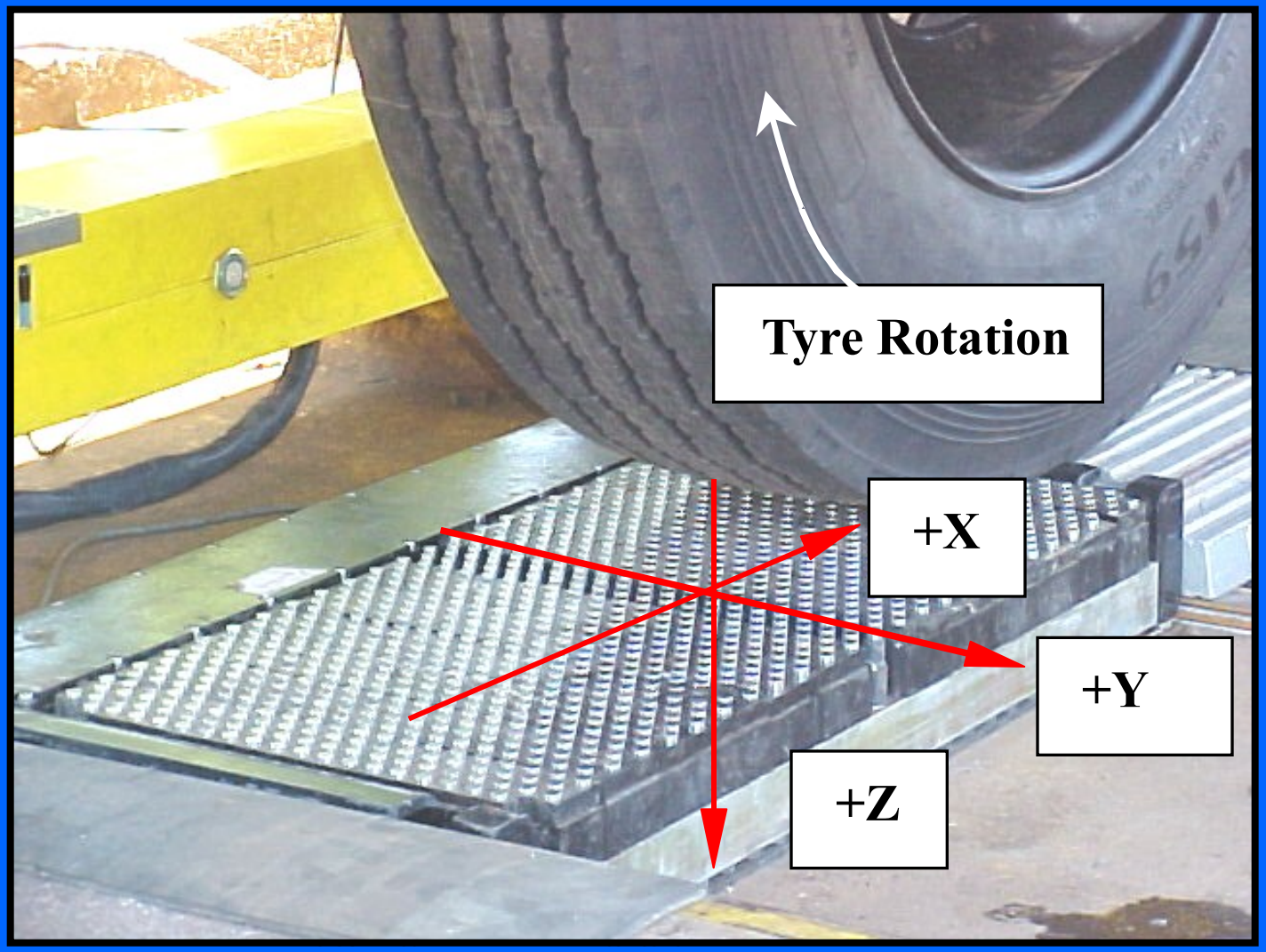




Stress Ratio: 10:3:1



SAE sign convention used during SIM measurements. X-Longitudinal, Y-Lateral and Z -Vertical loads/stresses.

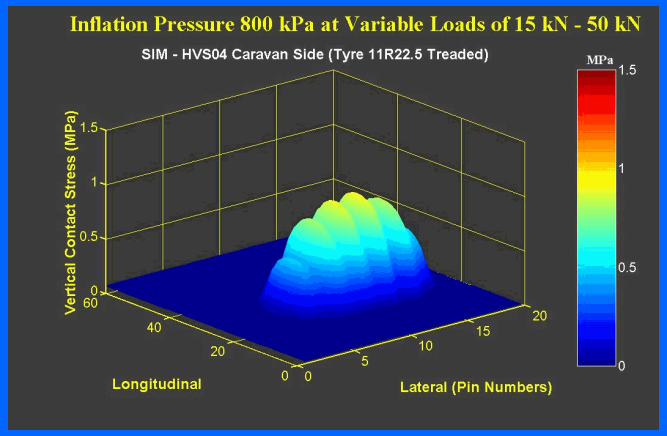


One of the Problems: Dynamic Loading….

Current design assumptions: Static-Uniform-1D

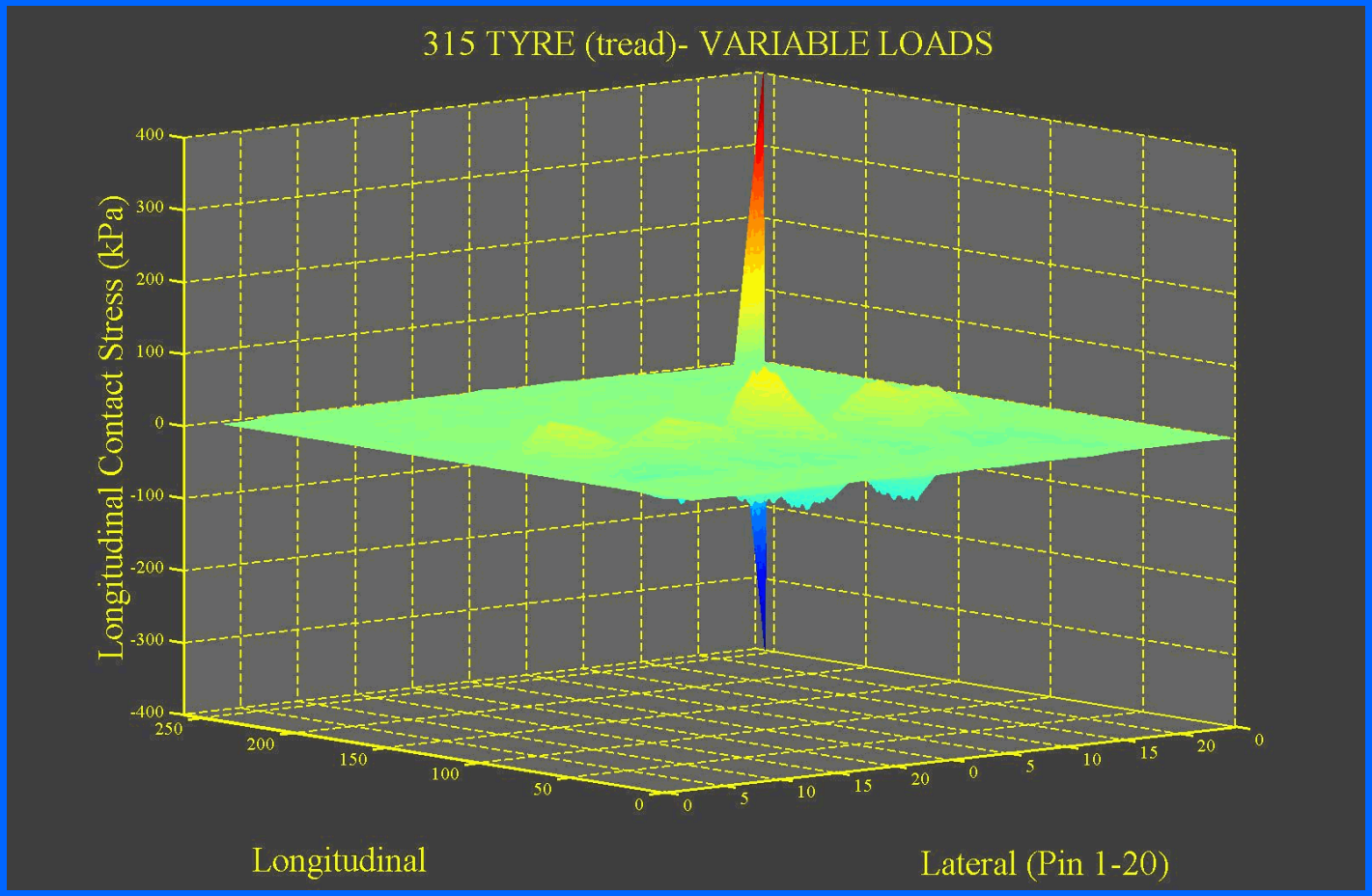
20 kN, 520 kPa

Reality: 3D Dynamic

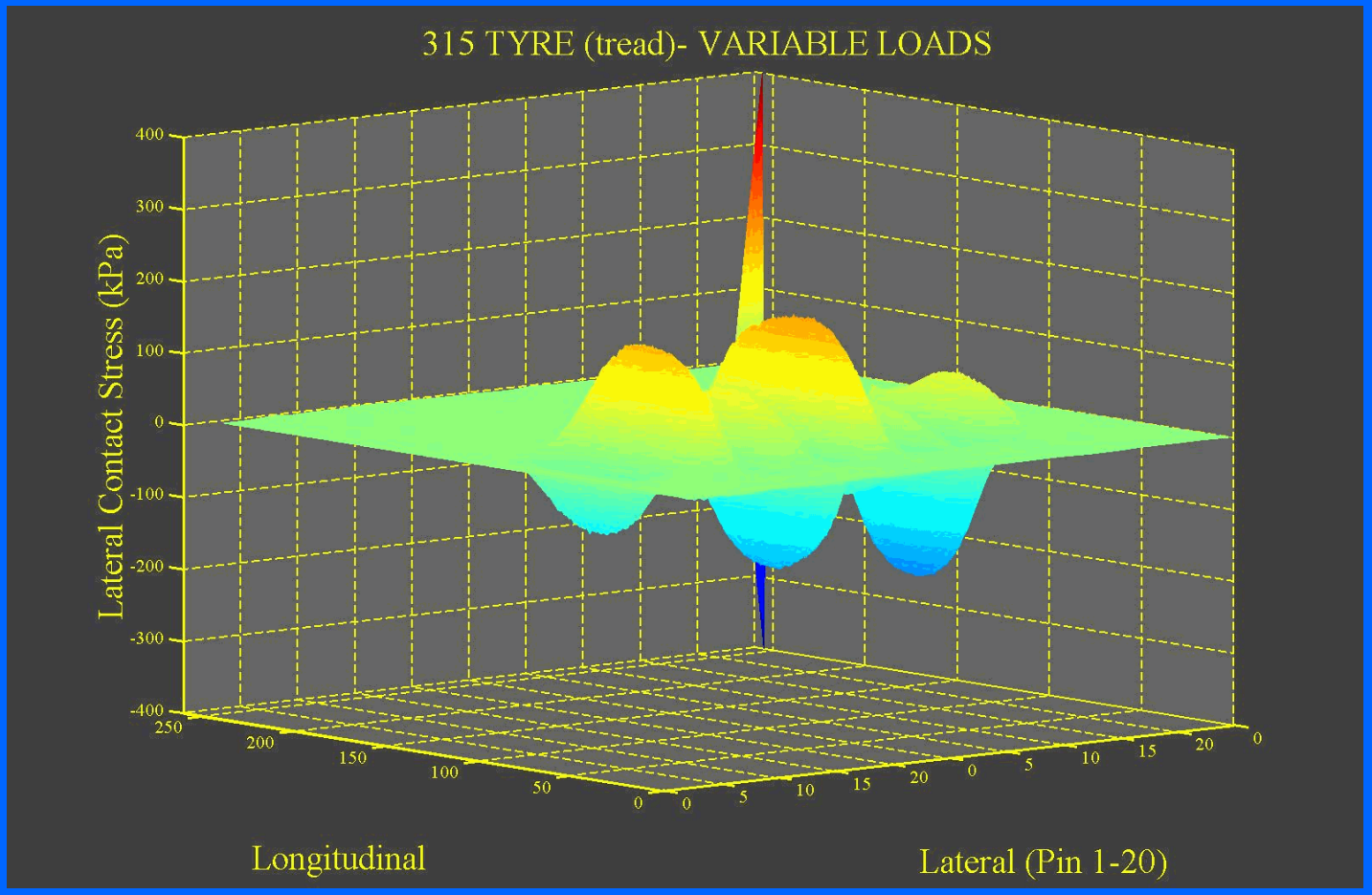


3D-Contact stresses

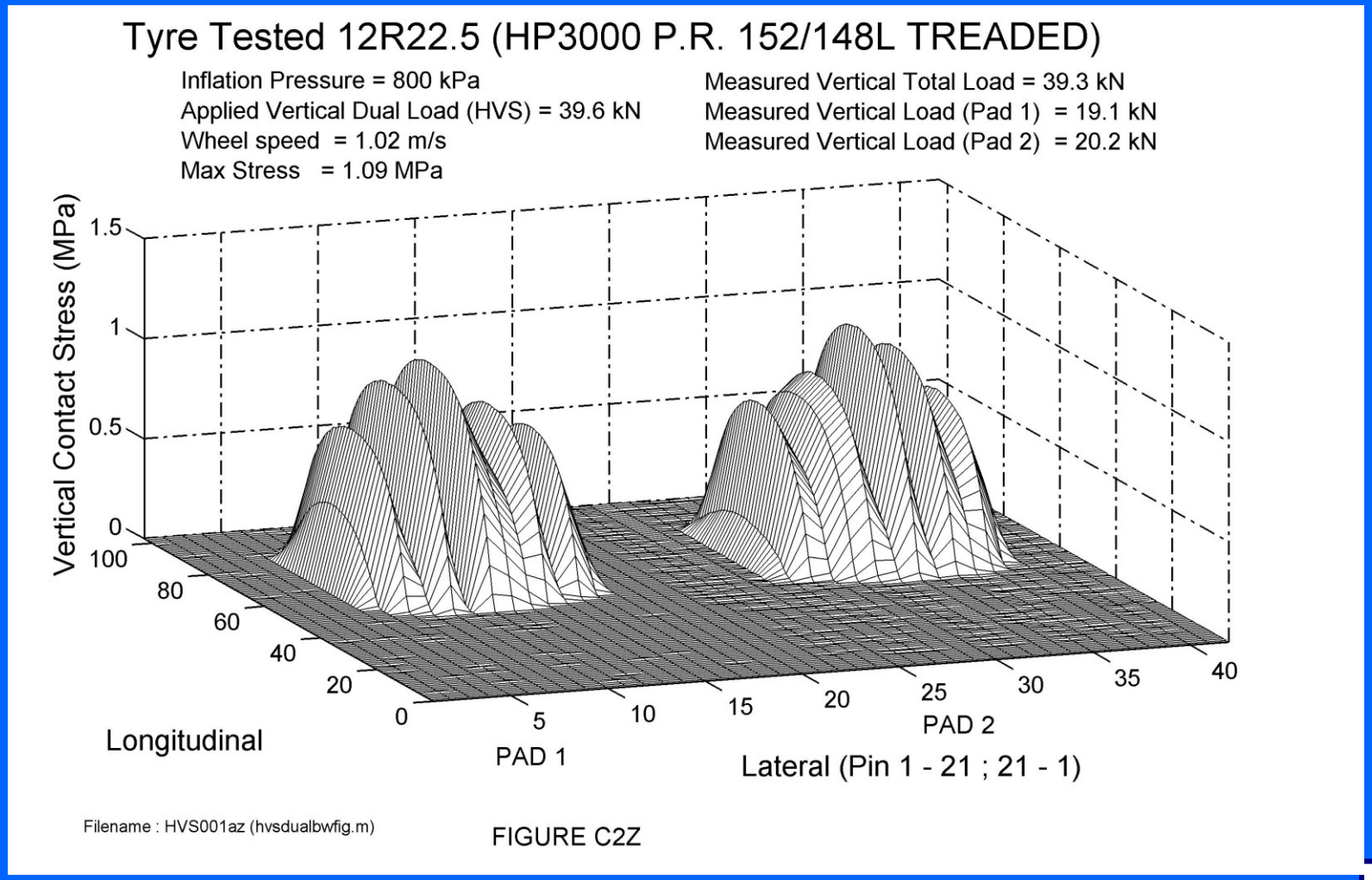
Longitudinal (X) - Stresses



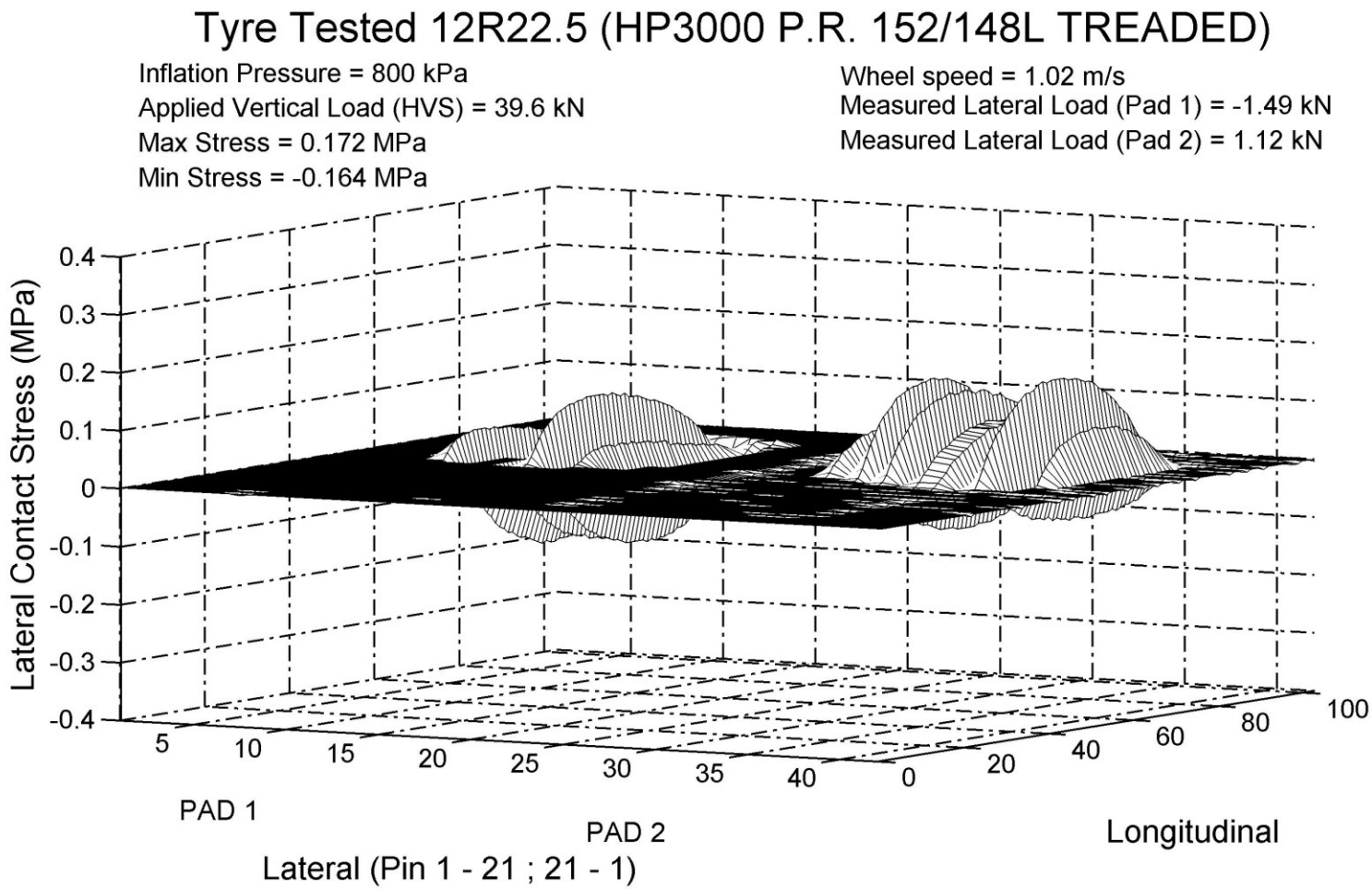
Lateral (Y) - Stresses



Typical SIM Data – Z-Vertical Stress - Full Scale



Typical SIM Data – Y-Lateral Stress - Full Scale



Filename : HVS001ay (hvsdualbwfig.m)

FIGURE C2Y

Typical SIM Data – X-Longitudinal Stress - Full Scale

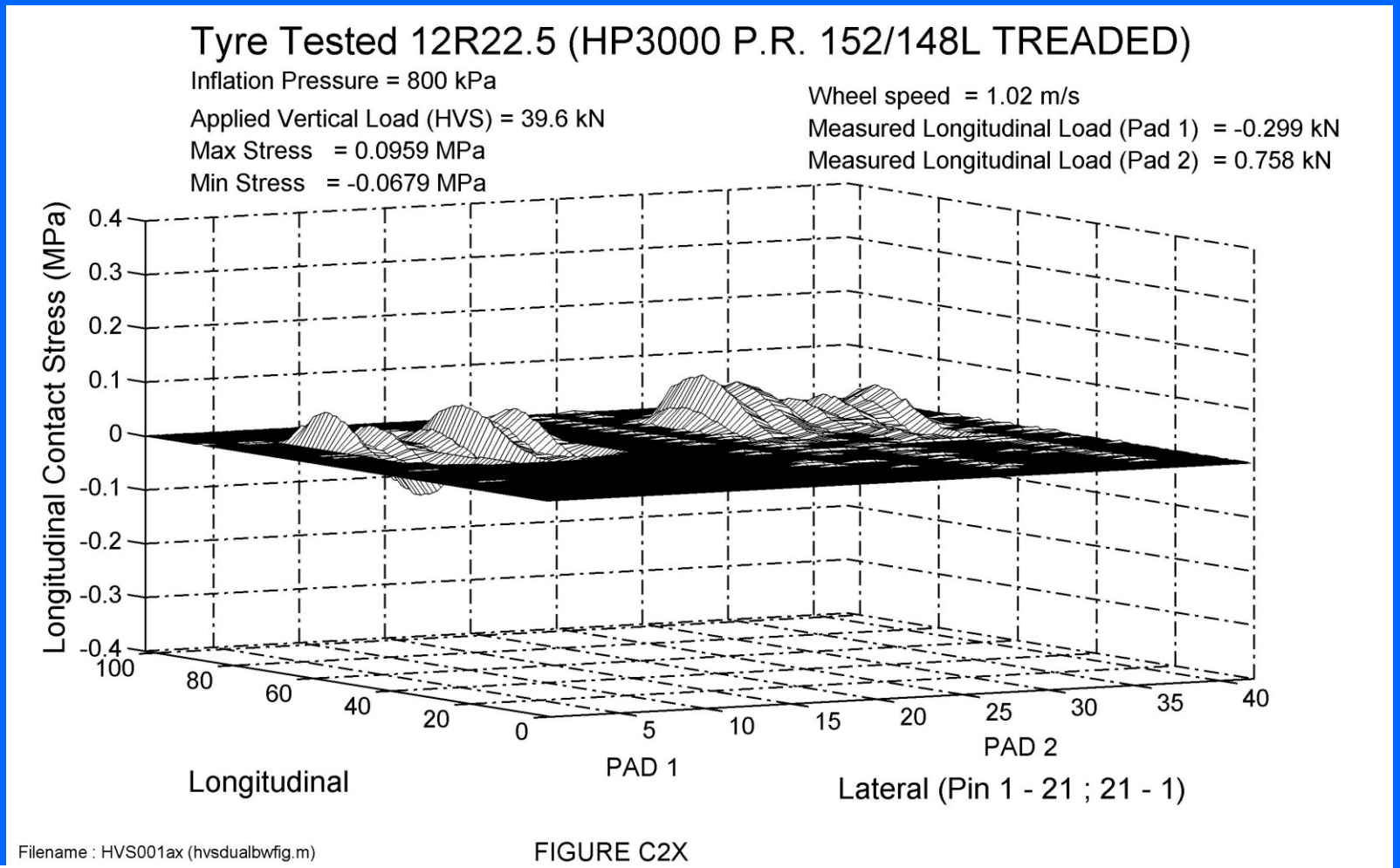
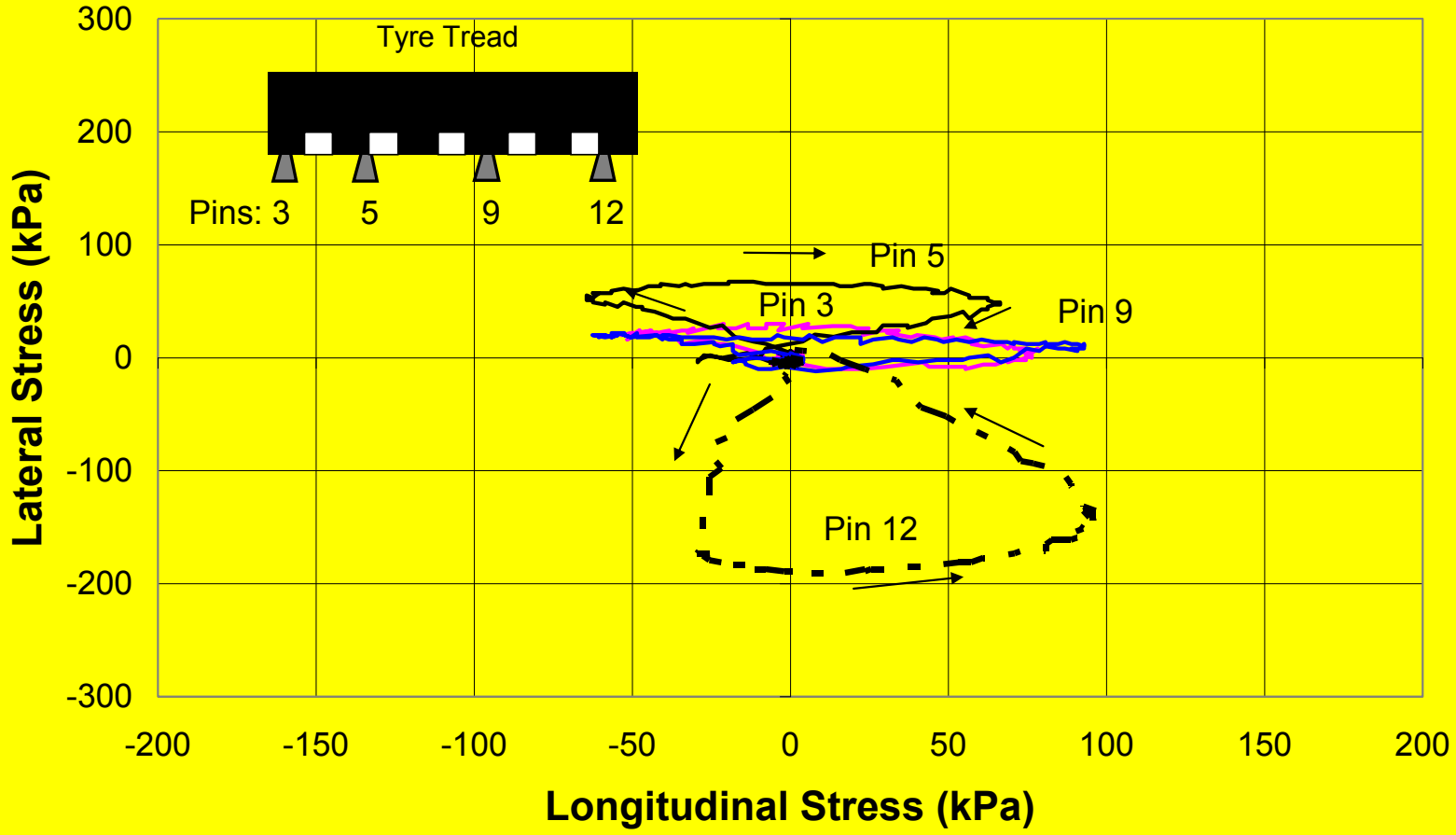
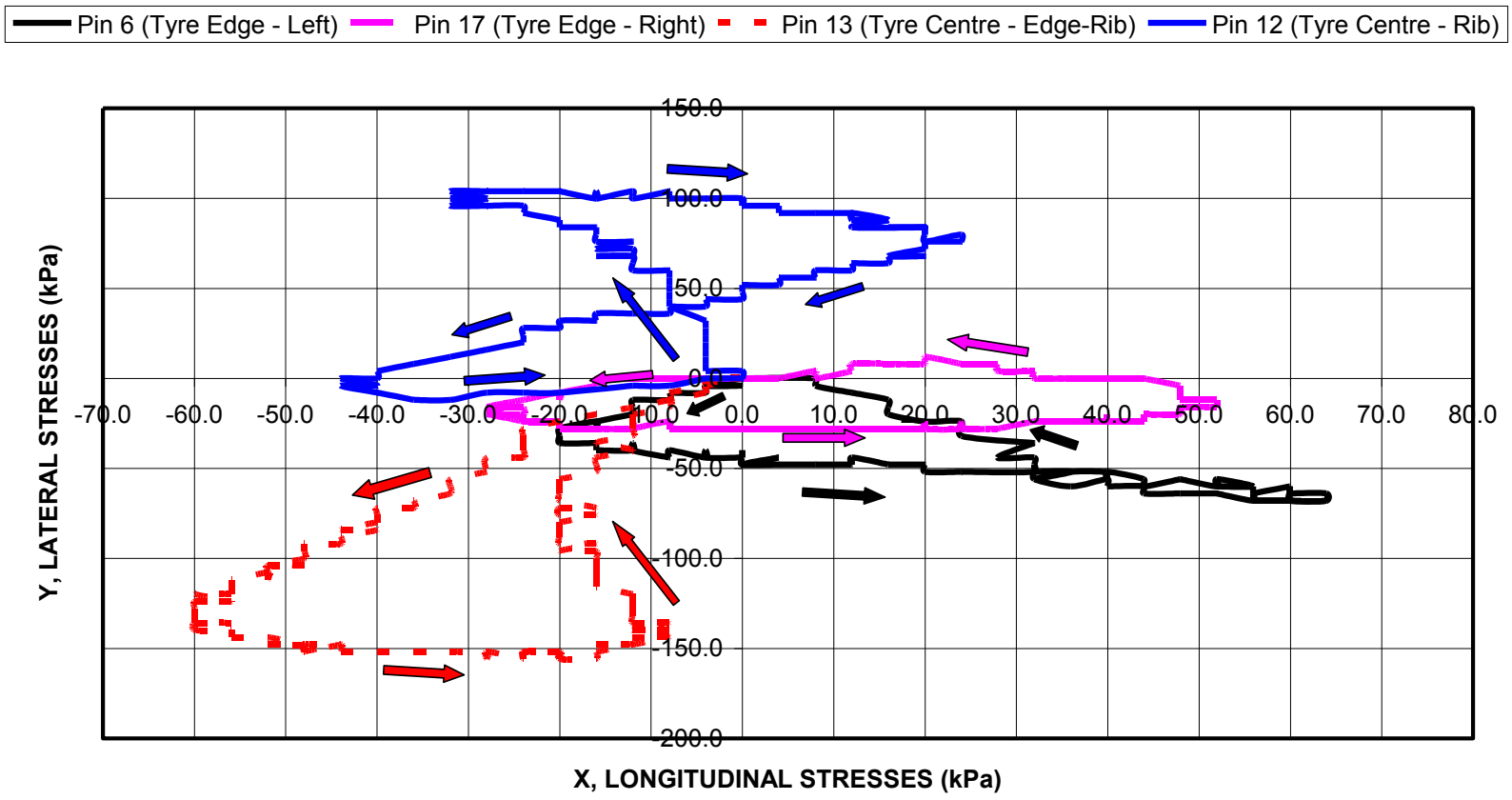


FIGURE C2X

Excursion Curves (Douglas, Siegfried, 2000)

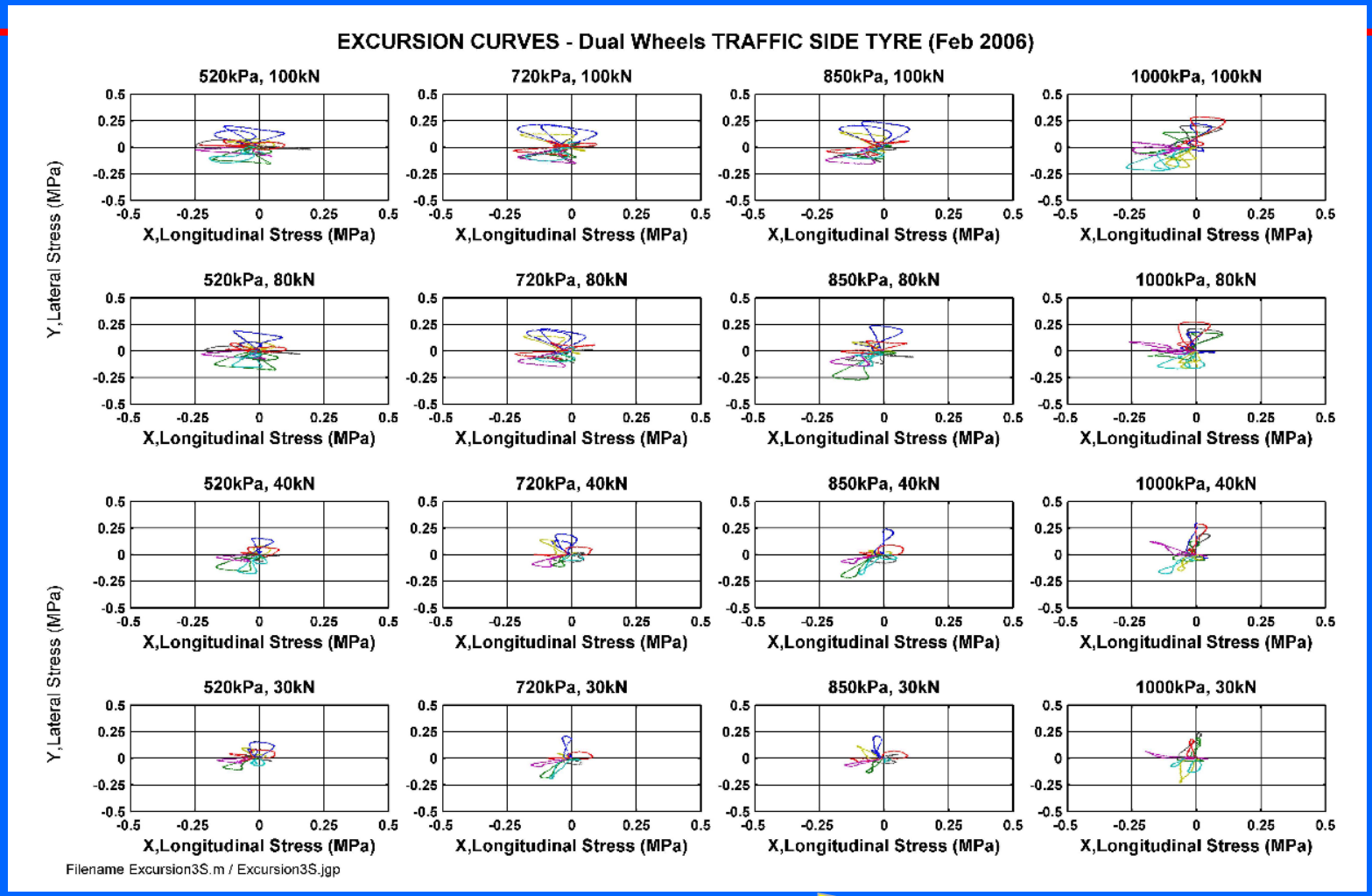


X, Y - Excursion Curves



“Finger printing” – Excursion Curves - (X,Y) Stresses-12R22.5 HVS Tyre

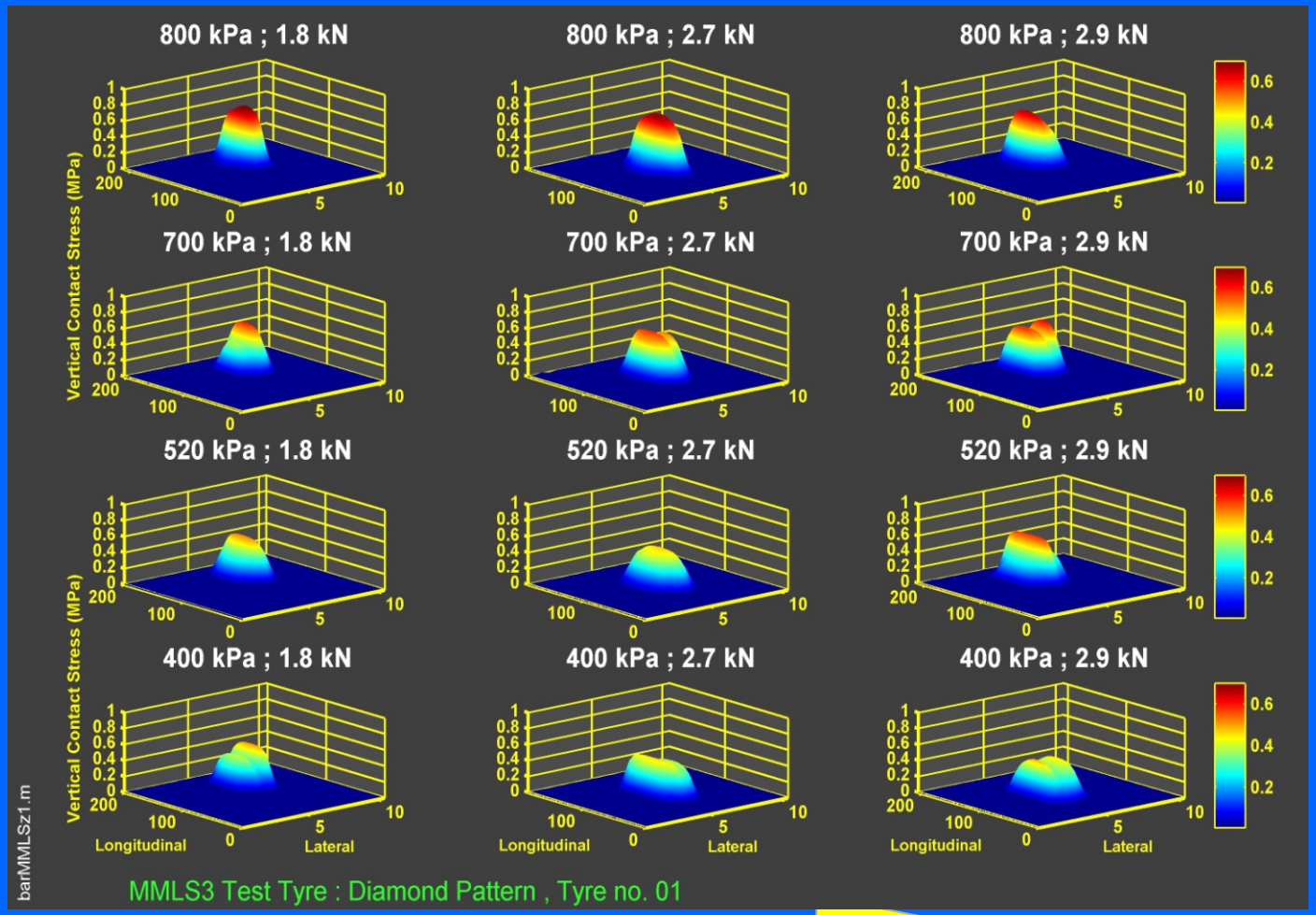
TYRE LOAD



INFLATION PRESSURE

"FINGER PRINTING" - VERTICAL CONTACT STRESS (MMLS3)

TYRE LOAD



INFLATION PRESSURE

3D Contact Stresses: MMLS3 – SIM Device – Data used in this Study

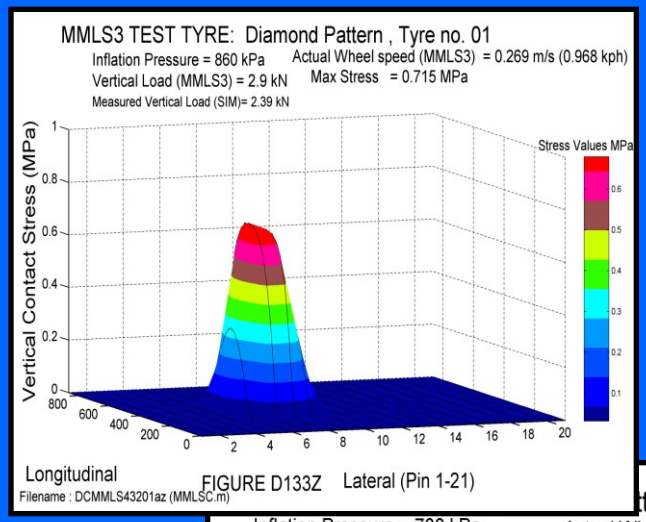


FIGURE D133Z

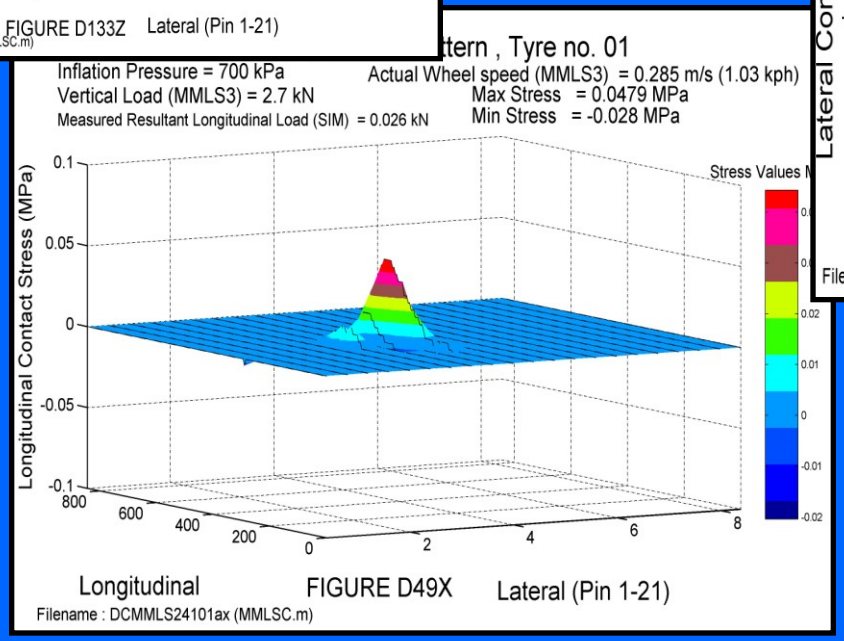


FIGURE D49X

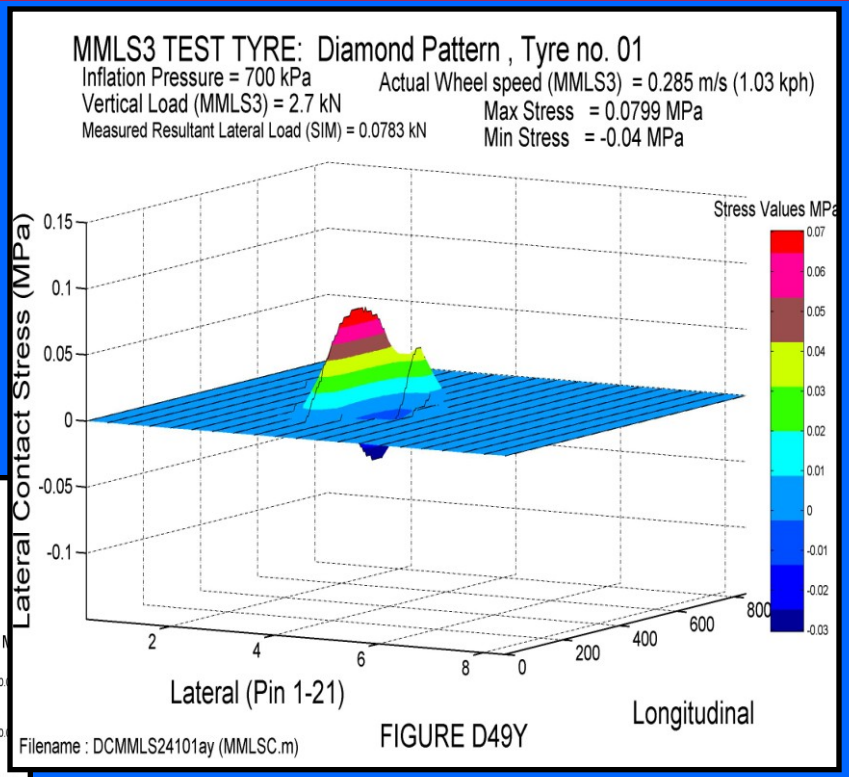


FIGURE D49Y

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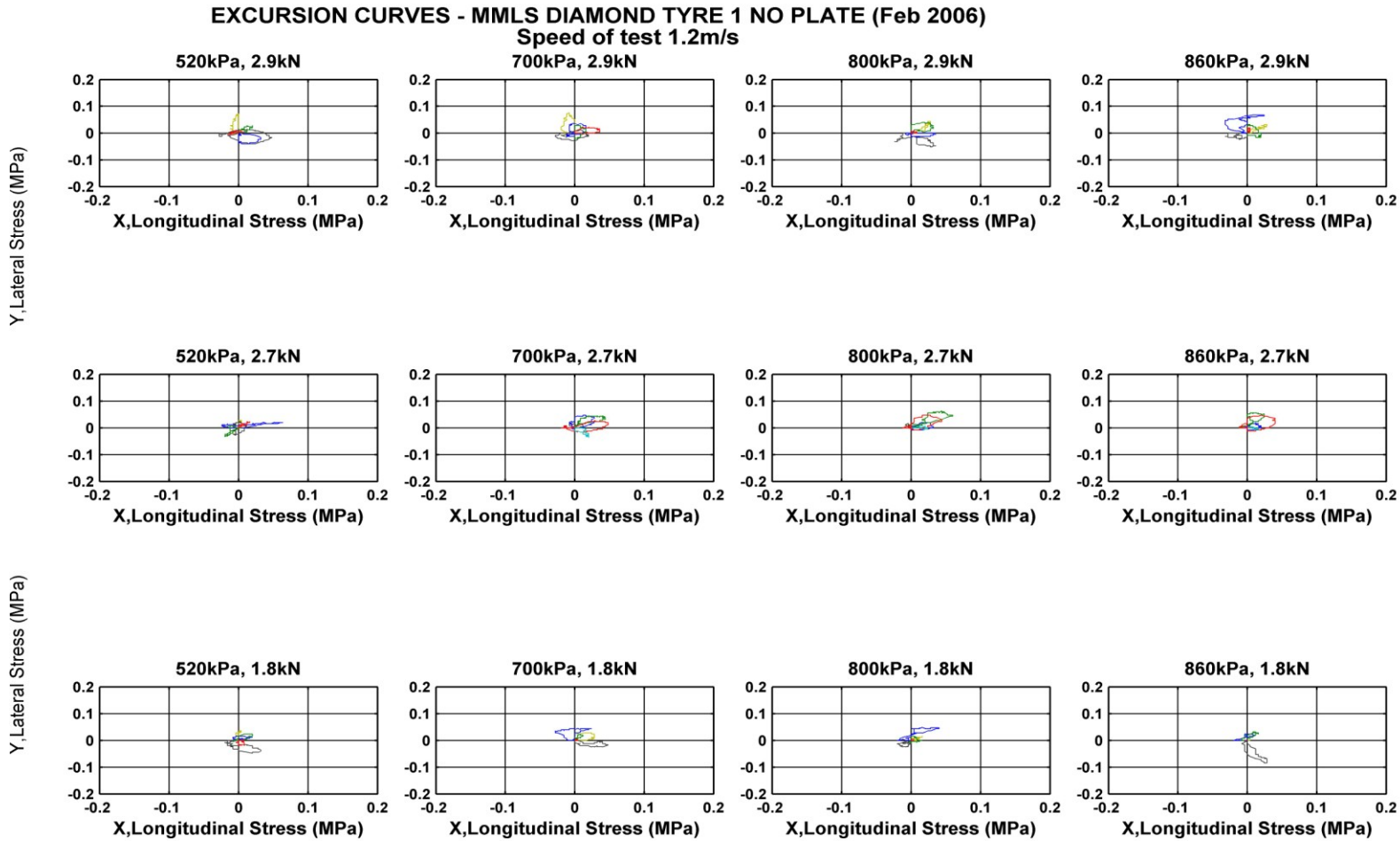
Excursion Curves – MMLS3 test tyre



Filename ExDiamond1S.m / ExDiamond1Sa.jpg

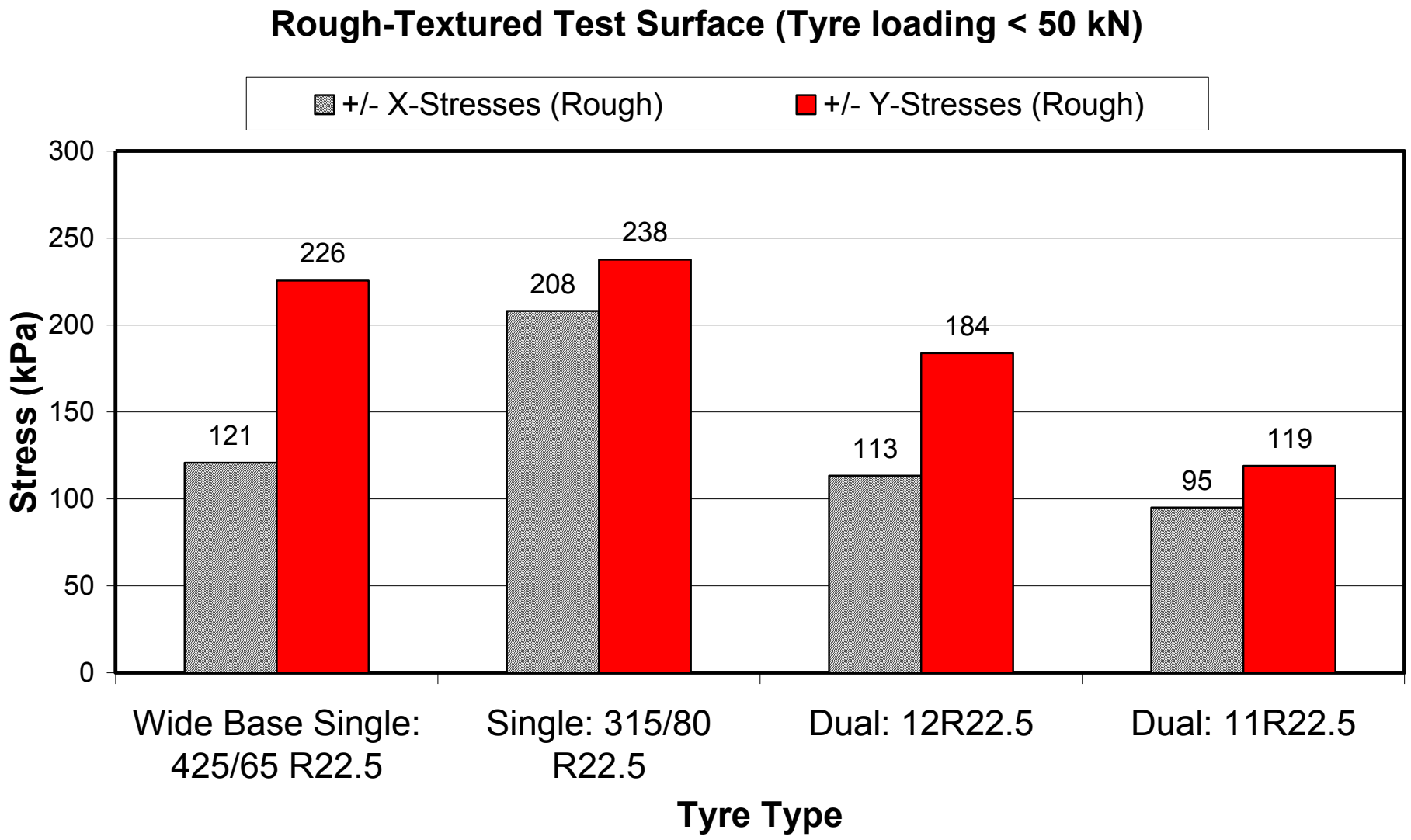
Table 1: Summary of Z,X &Y Stresses

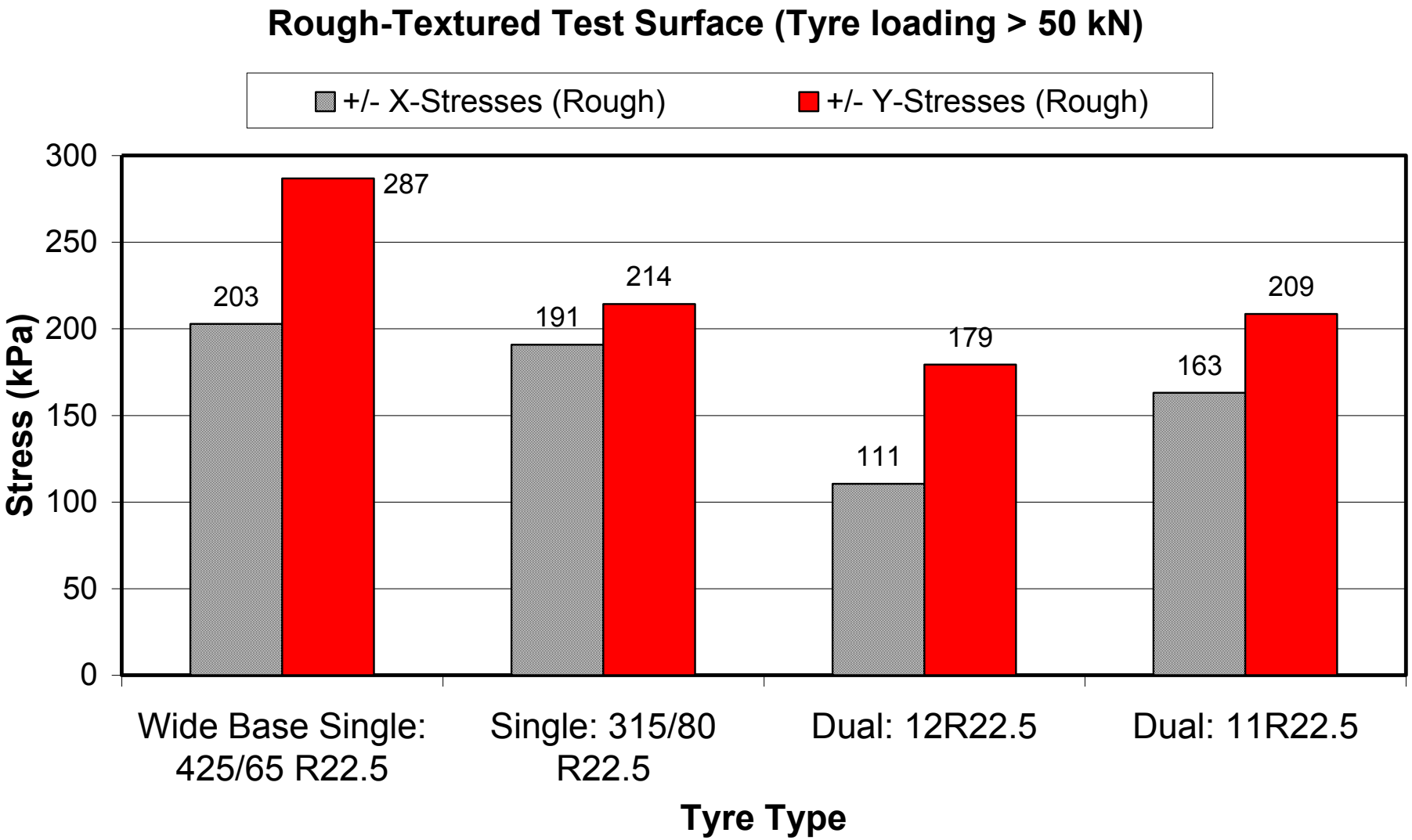
TYPE OF TYRE TESTED	TYRE LOADING RANGE (kN) - (HVS @ 1.22 km/h)	INFLATION PRESSURE RANGE (kPa)	Max Z Stress -min (kPa)	Max Z Stress - max (kPa)	Max Z Ave Stress (kPa)	CoV (%)	+/- X-Stresses		+/- Y-Stresses		Difference of Y-Stress relative to X-Stress (%)	Surface (SIM) *
							Average (kPa)	CoV (%)	Average (kPa)	CoV (%)		
LOWER LOADS & ROUGH-TEXTURED (RT) SIM TEST SURFACE:												
Wide Base Single: 425/65 R22.5	25 to 50	500 to 1000	978	1843	1409	16	121	33	226	15	86.7	*RT (12)*
Single: 315/80 R22.5	20 to 35	520 to 1000	759	1994	1244	31	208	29	238	17	14.2	*RT*
Dual: 12R22.5	30 to 40	520 to 1000	799	1207	1041	13	113	12	184	7	62.3	*RT*
Dual: 11R22.5	30 to 40	420 to 800	759	1016	898	12	95	16	119	11	25.3	*RT*
		Average:	***823.8***	***1515.0***	***1147.8***	***17.9***	***134.3***	***22.4***	***191.4***	***12.4***	***47.1***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	1.8 to 2.7	520 to 860	455	967	722	16	40	21	63	24	57.5	*RT*
		RATIO:FULL SCALE/MMLS3	***1.8***	***1.6***	***1.6***	***1.1***	***3.4***	***1.1***	***3.0***	***0.5***	***0.8***	
HIGHER LOADS & ROUGH-TEXTURED (RT) SIM TEST SURFACE:												
Wide Base Single: 425/65 R22.5	75 to 100	500 to 1000	1663	2204	1953	9	203	19	287	11	41.4	*RT*
Single: 315/80 R22.5	50 to 100	520 to 1000	863	1994	1375	27	191	38	214	32	12.3	*RT*
Dual: 12R22.5	50 to 100	520 to 1000	803	1398	1097	13	111	12	179	12	62.2	*RT*
Dual: 11R22.5	30 to 40	420 to 800	1118	1485	1289	13	163	16	209	24	27.9	*RT*
		Average:	***1111.8***	***1770.3***	***1428.3***	***15.4***	***166.8***	***21.3***	***222.2***	***19.7***	***36.0***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	1.8 to 2.7	520 to 860	455	967	722	16	40	21	63	24	57.5	*RT*
		RATIO:FULL SCALE/MMLS3	***2.4***	***1.8***	***2.0***	***1.0***	***4.2***	***1.0***	***3.5***	***0.8***	***0.6***	
LOWER LOADS & SMOOTH (S) SIM TEST SURFACE:												
Single: 315/80 R22.5	50 to 100	520 to 1000	863	2465	1495	35	141	33	204	31	44	*S*
Dual: 12R22.5	50 to 100	520 to 1000	935	1586	1313	15	95	17	135	9	42	*S*
		Average:	***899.0***	***2025.5***	***1403.9***	***25.0***	***118.0***	***24.7***	***169.4***	***20.0***	***43.4***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	2.7	700 to 860	727	1187	937	11	19	16	39	13	105	*S*
		RATIO:FULL SCALE/MMLS3	***1.2***	***1.7***	***1.5***	***2.3***	***6.2***	***1.5***	***4.3***	***1.5***	***0.4***	
HIGHER LOADS & SMOOTH (S) SIM TEST SURFACE:												
Single: 315/80 R22.5	50 to 100	520 to 1000	1426	2561	1979	24	150	32	257	20	71	*S*
Dual: 12R22.5	50 to 100	520 to 1000	1127	1926	1493	16	122	5	140	7	15	*S*
		Average:	***1276.5***	***2243.5***	***1735.8***	***20.4***	***136.0***	***18.4***	***198.3***	***13.7***	***42.8***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	2.7	700 to 860	727	1187	937	11	19	16	39	13	105	*S*
		RATIO:FULL SCALE/MMLS3	***1.8***	***1.9***	***1.9***	***1.9***	***7.2***	***1.2***	***5.1***	***1.1***	***0.4***	

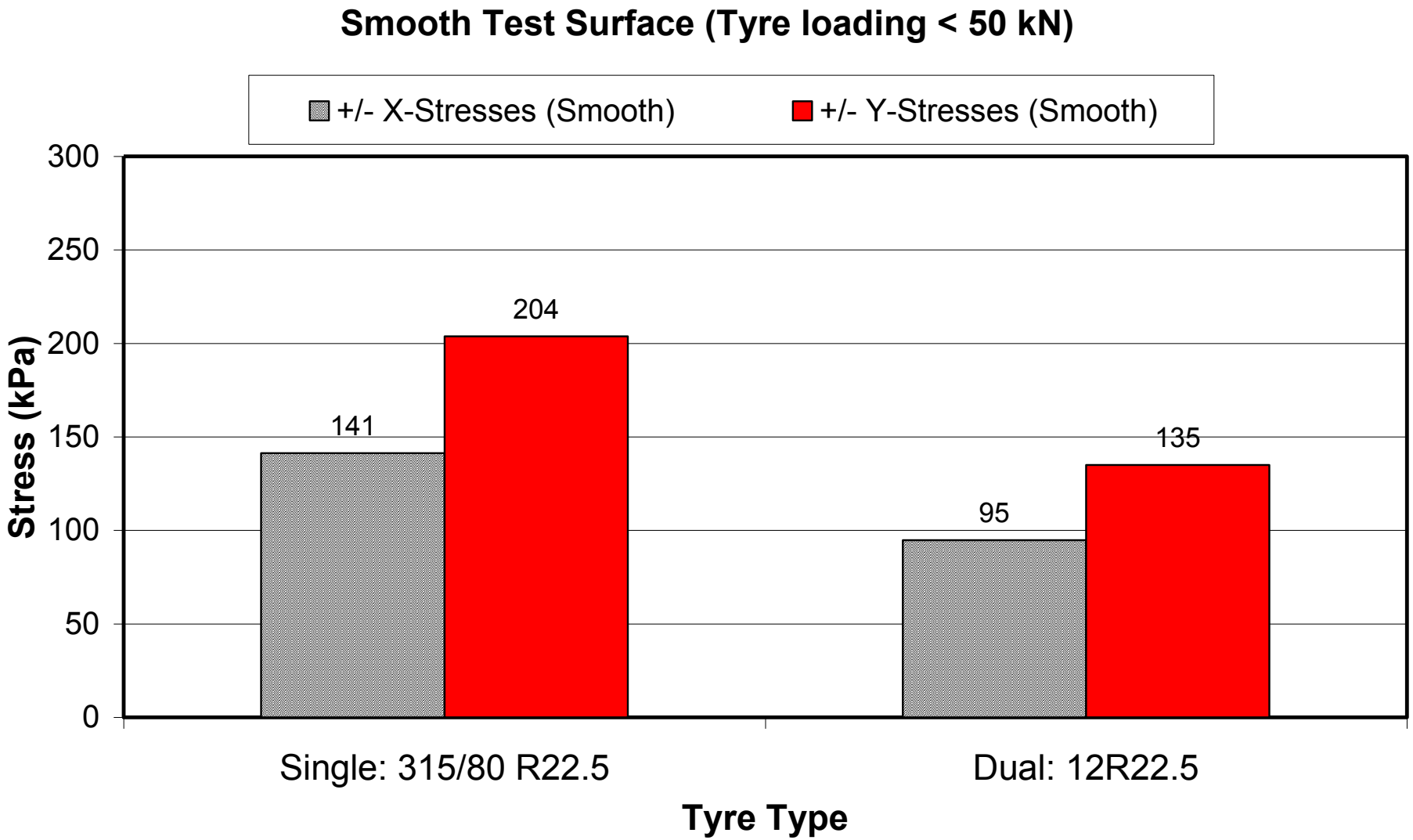
* Legend: RT = Rough-Textured SIM test surface, and S = Smooth SIM test surface. Note:The given "Z Stress" represents the Maximum Vertical Contact Stress (MVCS) for each case.

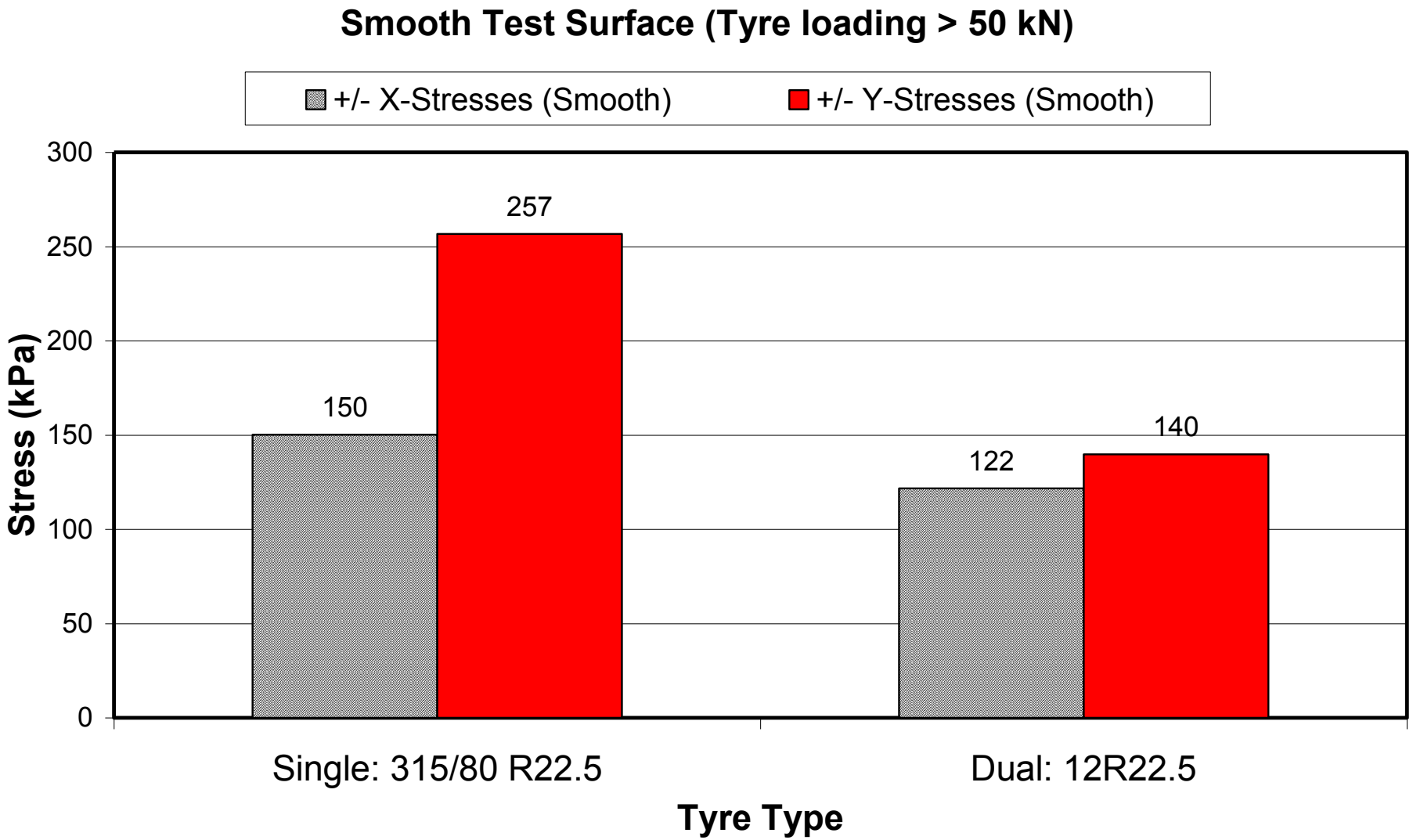
Table 1: Summary of Z,X &Y Stresses

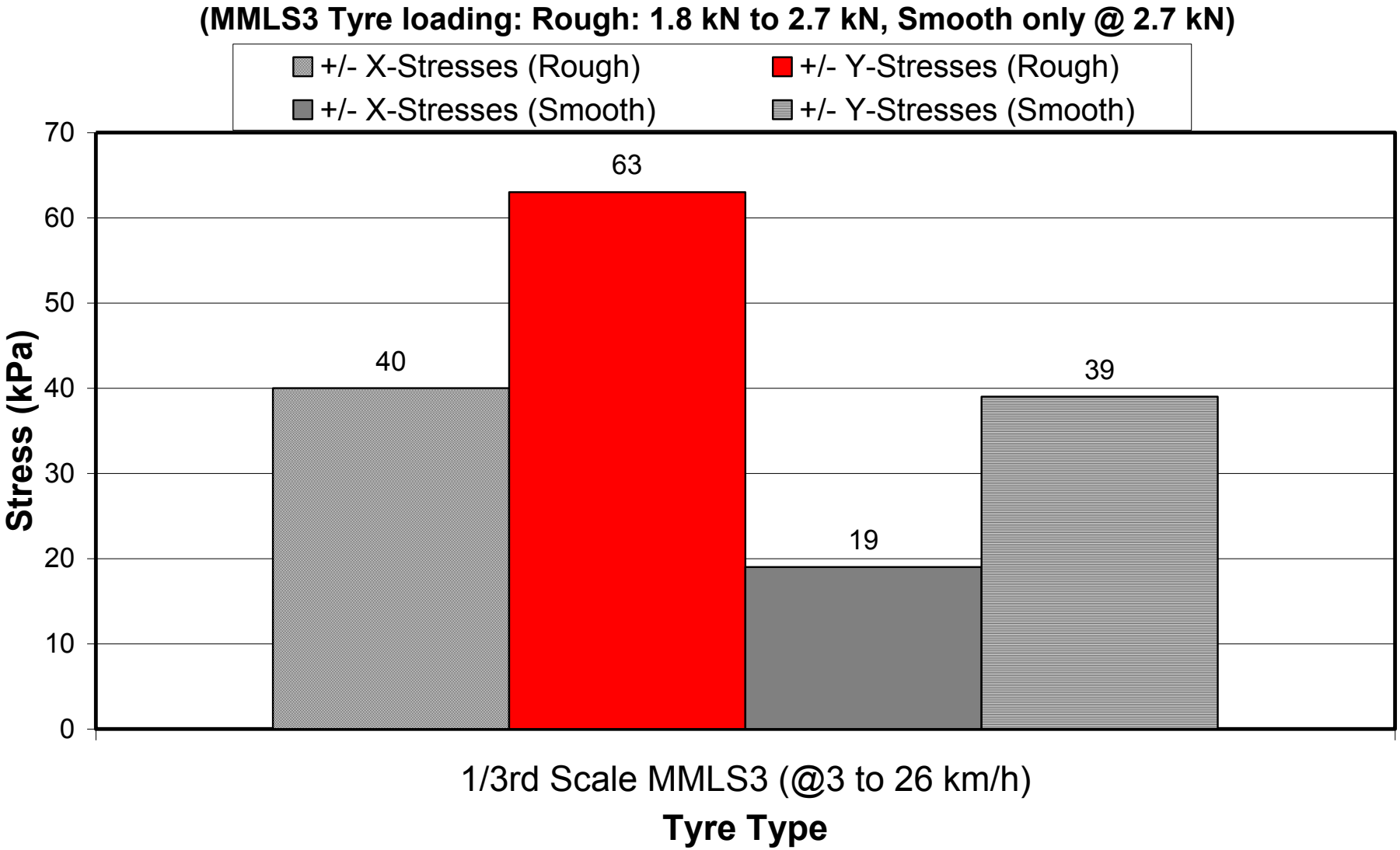
ax Z ess - (kPa)	Max Z Ave Stress (kPa)	CoV (%)	+/- X-Stresses		+/- Y-Stresses		Difference of Y-Stress relative to X-Stress (%)	Surface (SIM) *
			Average (kPa)	*CoV (%)*	Average (kPa)	*CoV (%)*		
843	1409	16	121	33	226	15	86.7	*RT (12)*
994	1244	31	208	29	238	17	14.2	*RT*
207	1041	13	113	12	184	7	62.3	*RT*
016	898	12	95	16	119	11	25.3	*RT*
15.0	***1147.8***	***17.9***	***134.3***	***22.4***	***191.4***	***12.4***	***47.1***	
67	722	16	40	21	63	24	57.5	*RT*
.6	***1.6***	***1.1***	***3.4***	***1.1***	***3.0***	***0.5***	***0.8***	
204	1953	9	203	19	287	11	41.4	*RT*
994	1375	27	191	38	214	32	12.3	*RT*
898	1097	13	111	12	179	12	62.2	*RT*
485	1289	13	163	16	209	24	27.9	*RT*
70.3	***1428.3***	***15.4***	***166.8***	***21.3***	***222.3***	***10.7***	***36.0***	


Rough-Textured Test Surface (Tyre loading < 50 kN)
+/- X-Stresses (Rough)
+/- Y-Stresses (Rough)
Stress (kPa)
300
250
200
150
100
50
0
121
226
208
238
113
184
95
119
Wide Base Single: 425/65 R22.5
Single: 315/80 R22.5
Dual: 12R22.5
Dual: 11R22.5
Tyre Type

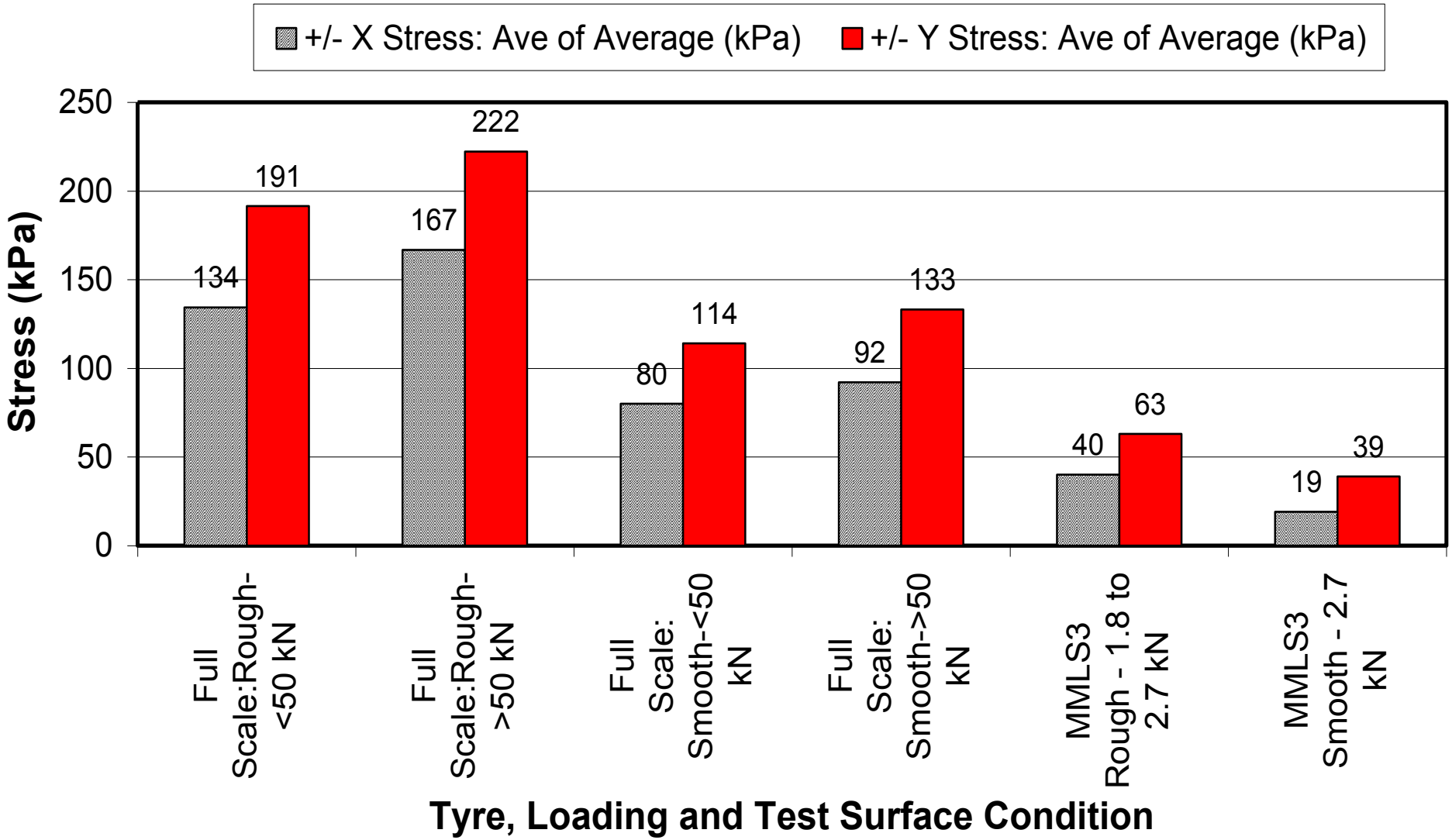

Rough-Textured Test Surface (Tyre loading > 50 kN)
+/- X-Stresses (Rough)
+/- Y-Stresses (Rough)
Stress (kPa)
300
250
200
150
100
50
0
203
287
191
214
111
179
163
209
Wide Base Single: 425/65 R22.5
Single: 315/80 R22.5
Dual: 12R22.5
Dual: 11R22.5
Tyre Type


Smooth Test Surface (Tyre loading < 50 kN)
+/- X-Stresses (Smooth)
+/- Y-Stresses (Smooth)
Stress (kPa)
300
250
200
150
100
50
0
141
204
95
135
Single: 315/80 R22.5
Dual: 12R22.5
Tyre Type

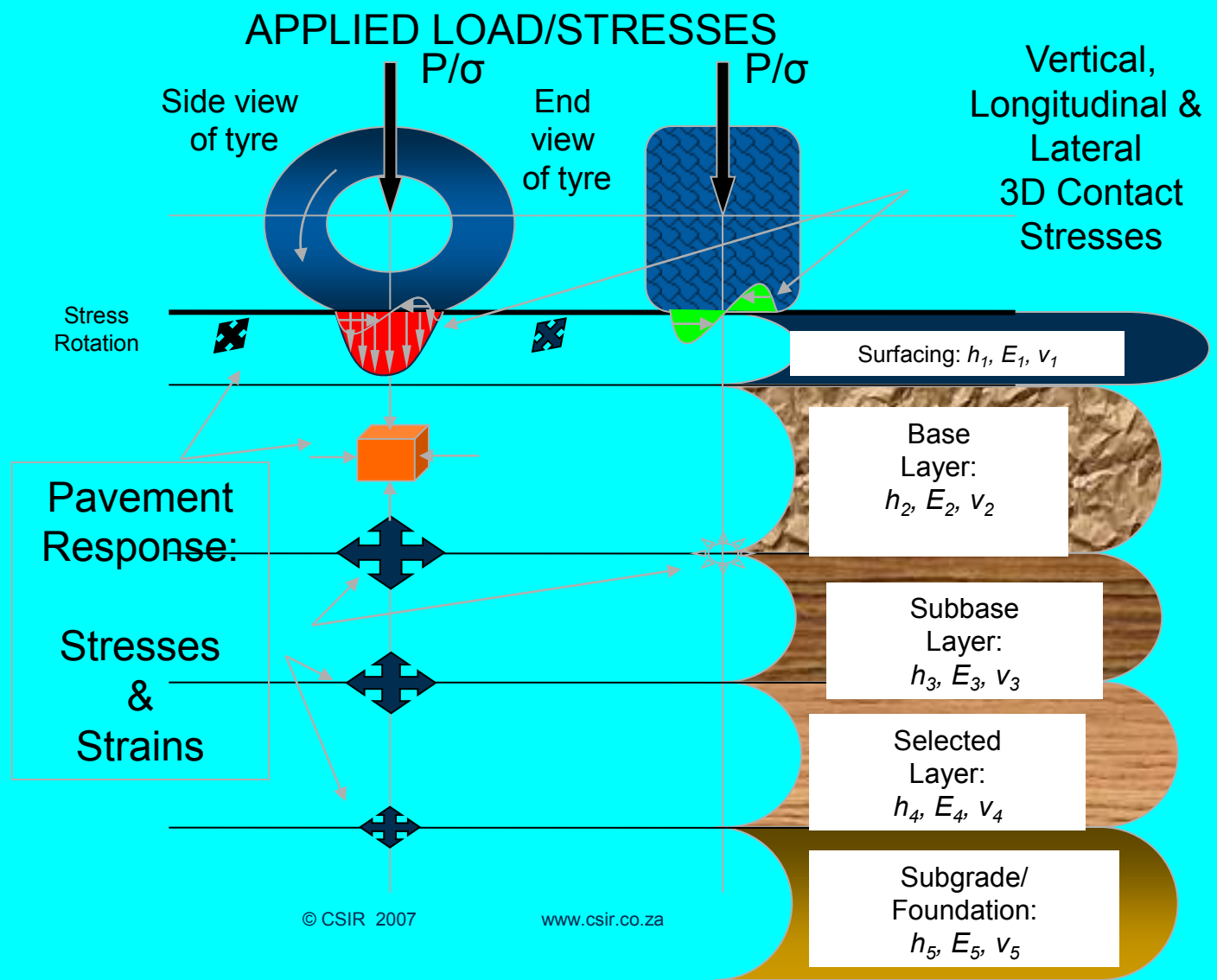

Smooth Test Surface (Tyre loading > 50 kN)
+/- X-Stresses (Smooth)
+/- Y-Stresses (Smooth)
Stress (kPa)
300
250
200
150
100
50
0
257
150
140
122
Single: 315/80 R22.5
Dual: 12R22.5
Tyre Type


(MMLS3 Tyre loading: Rough: 1.8 kN to 2.7 kN, Smooth only @ 2.7 kN)
+/- X-Stresses (Rough)
+/- Y-Stresses (Rough)
+/- X-Stresses (Smooth)
+/- Y-Stresses (Smooth)
Stress (kPa)
70
60
50
40
30
20
10
0
63
40
19
39
1/3rd Scale MMLS3 (@3 to 26 km/h)
Tyre Type

Comparison of Average Horizontal Stresses



Road/Tyre Interaction and Mechanistic Design



Major Conclusions (1):

- For free-rolling pneumatic rubber tyres the tangential lateral and tangential longitudinal (horizontal) contact stresses were measured with the Stress-In-Motion (SIM) device (in addition to the vertical stresses);
- The Excursion Curve (EC) methodology used here allows for improved visual understanding of the interaction between the tangential (horizontal) X and Y – Stresses of free-rolling rubber tyres;

Major Conclusions (2):

- The lateral Y – Stresses are generally higher than the longitudinal X – Stresses (approximately 30 to 50 per cent higher);
- The X, Y – Stresses on a *relatively* *rough-textured (RT)* pavement surface appear to be approximately 16 per cent to 32 per cent *higher* than those found on a *relatively* *smooth (S) surface*.

Major Conclusions (3):

- Depending on loading levels, the X, Y – Stresses produced by the 1/3rd scale MMLS3 tyre (Diamond, square profile) are, on average, only approximately one quarter to one third of those produced by full-scale tyres on a relatively rough-textured (RT) test surface;

Major Recommendations (1):

- Further studies on the effect of road texture on the tyre contact stresses with improved measuring equipment, when this becomes available;

- Planning of potential APT (i.e. HVS and MMLS3 tests) to evaluate comparative vertical rutting (i.e. plastic deformation) development on different surface texture conditions;

Major Recommendations (2):

- TRH 3 (TRH 3, 2007) - Equivalent Light Vehicle (ELV) to traffic loading on seals could be challenged;
- Use of the X, Y - Stress data in this paper towards the improved micro-mechanic modelling of road surfacings in southern Africa, including Interface Shear Energy; (Douglas et al, 2003)

Major Recommendations (3):

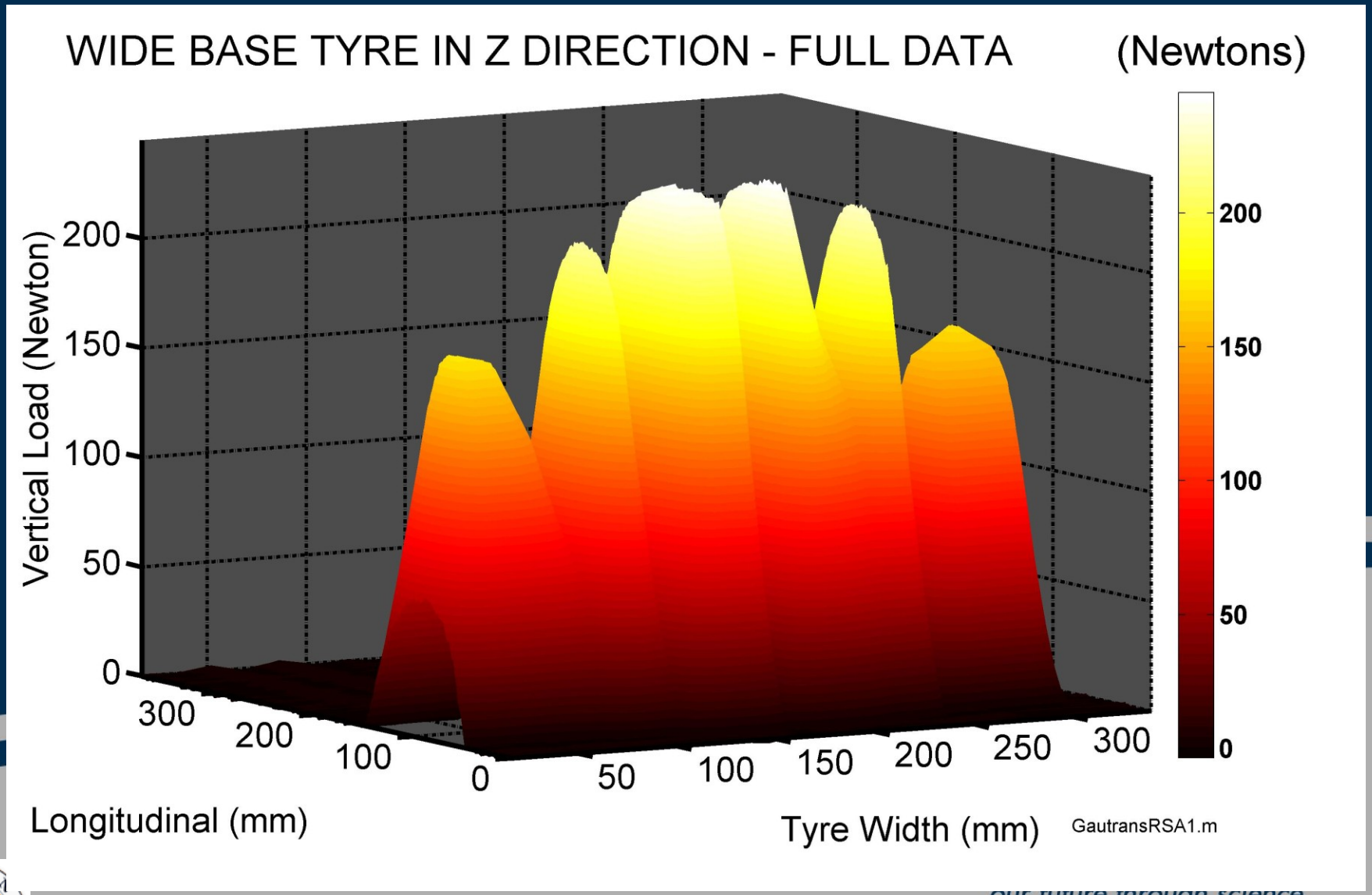
- Study and quantification of the effects of tyre tread pattern;
- tyre torque, i.e. acceleration (driven), deceleration (braking) and
- cornering (turning, scuffing (or slippage):
- Time for a more rational mechanistic road surface design methodology based on micro-mechanics ?

Thank You for listening…!

Thank You for listening…!

TYPE OF TYRE TESTED	TYRE LOADING RANGE (kN) - (HVS @ 1.22 km/h)	INFLATION PRESSURE RANGE (kPa)	Maximum Vertical Contact Stress (MVCS)				+/- X-Stresses (Ave. Max Range)		+/- Y-Stresses (Ave. Max. Range)		Difference of Y-Stress relative to X-Stress (%)	Surface (SIM) and Number of Tests *
			Max Z Stress - min. of range (kPa)	Max Z Stress - max. of range (kPa)	Z Max. Ave. Stress (kPa)	*CoV (%)*	Average Max. (kPa)	*CoV (%)*	Average Max. (kPa)	*CoV (%)*		
LOWER LOADS & ROUGH-TEXTURED (RT) SIM TEST SURFACE:												
Wide Base Single: 425/65 R22.5	25 to 50	500 to 1000	978	1843	1409	16	121	33	226	15	86.7	*RT (12x3)*
Single: 315/80 R22.5	20 to 35	520 to 1000	759	1994	1244	31	208	29	238	17	14.2	*RT (8x3)*
Dual: 12R22.5	30 to 40	520 to 1000	799	1207	1041	13	113	12	184	7	62.3	*RT (9x3)*
Dual: 11R22.5	30 to 40	420 to 800	759	1016	898	12	95	16	119	11	25.3	*RT (20x3)*
		Average:	***823.8***	***1515.0***	***1147.8***	***17.9***	***134.3***	***22.4***	***191.4***	***12.4***	***47.1***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	1.8 to 2.7	520 to 860	455	967	722	16	40	21	63	24	57.5	*RT (681)*
		RATIO: FULL SCALE/MMLS3	***1.8***	***1.6***	***1.6***	***1.1***	***3.4***	***1.1***	***3.0***	***0.5***	***0.8***	
HIGHER LOADS & ROUGH-TEXTURED (RT) SIM TEST SURFACE:												
Wide Base Single: 425/65 R22.5	75 to 100	500 to 1000	1663	2204	1953	9	203	19	287	11	41.4	*RT (11x3)*
Single: 315/80 R22.5	50 to 100	520 to 1000	863	1994	1375	27	191	38	214	32	12.3	*RT (8x3)*
Dual: 12R22.5	50 to 100	520 to 1000	803	1398	1097	13	111	12	179	12	62.2	*RT (16x3)*
Dual: 11R22.5	70 to 100	420 to 800	1118	1485	1289	13	163	16	209	24	27.9	*RT (20x3)*
		Average:	***1111.8***	***1770.3***	***1428.3***	***15.4***	***166.8***	***21.3***	***222.2***	***19.7***	***36.0***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	1.8 to 2.7	520 to 860	455	967	722	16	40	21	63	24	57.5	*RT (681)*
		RATIO: FULL SCALE/MMLS3	***2.4***	***1.8***	***2.0***	***1.0***	***4.2***	***1.0***	***3.5***	***0.8***	***0.6***	
LOWER LOADS & SMOOTH (S) SIM TEST SURFACE:												
Single: 315/80 R22.5	50 to 100	520 to 1000	863	2465	1495	35	141	33	204	31	44	*S (8x3)*
Dual: 12R22.5	50 to 100	520 to 1000	935	1586	1313	15	95	17	135	9	42	*S (8x3)*
		Average:	***899.0***	***2025.5***	***1403.9***	***25.0***	***118.0***	***24.7***	***169.4***	***20.0***	***43.4***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	2.7	700 to 860	727	1187	937	11	19	16	39	13	105	*S (178)*
		RATIO: MMLS3/FULL SCALE	***1.2***	***1.7***	***1.5***	***2.3***	***6.2***	***1.5***	***4.3***	***1.5***	***0.4***	
HIGHER LOADS & SMOOTH (S) SIM TEST SURFACE:												
Single: 315/80 R22.5	50 to 100	520 to 1000	1426	2561	1979	24	150	32	257	20	71	*S (8x3)*
Dual: 12R22.5	50 to 100	520 to 1000	1127	1926	1493	16	122	5	140	7	15	*S (8x3)*
		Average:	***1276.5***	***2243.5***	***1735.8***	***20.4***	***136.0***	***18.4***	***198.3***	***13.7***	***42.8***	
1/3rd Scale MMLS3 (@3 to 26 km/h)	2.7	700 to 860	727	1187	937	11	19	16	39	13	105	*S (178)*
		RATIO: FULL SCALE/MMLS3	***1.8***	***1.9***	***1.9***	***1.9***	***7.2***	***1.2***	***5.1***	***1.1***	***0.4***	

* Legend: RT = Rough-Textured SIM test surface, and S = Smooth SIM test surface. Note:The given "Z Stress" represents the Maximum Vertical Contact Stress (MVCS) for each case. RT (Number of tests), S (Number of tests)



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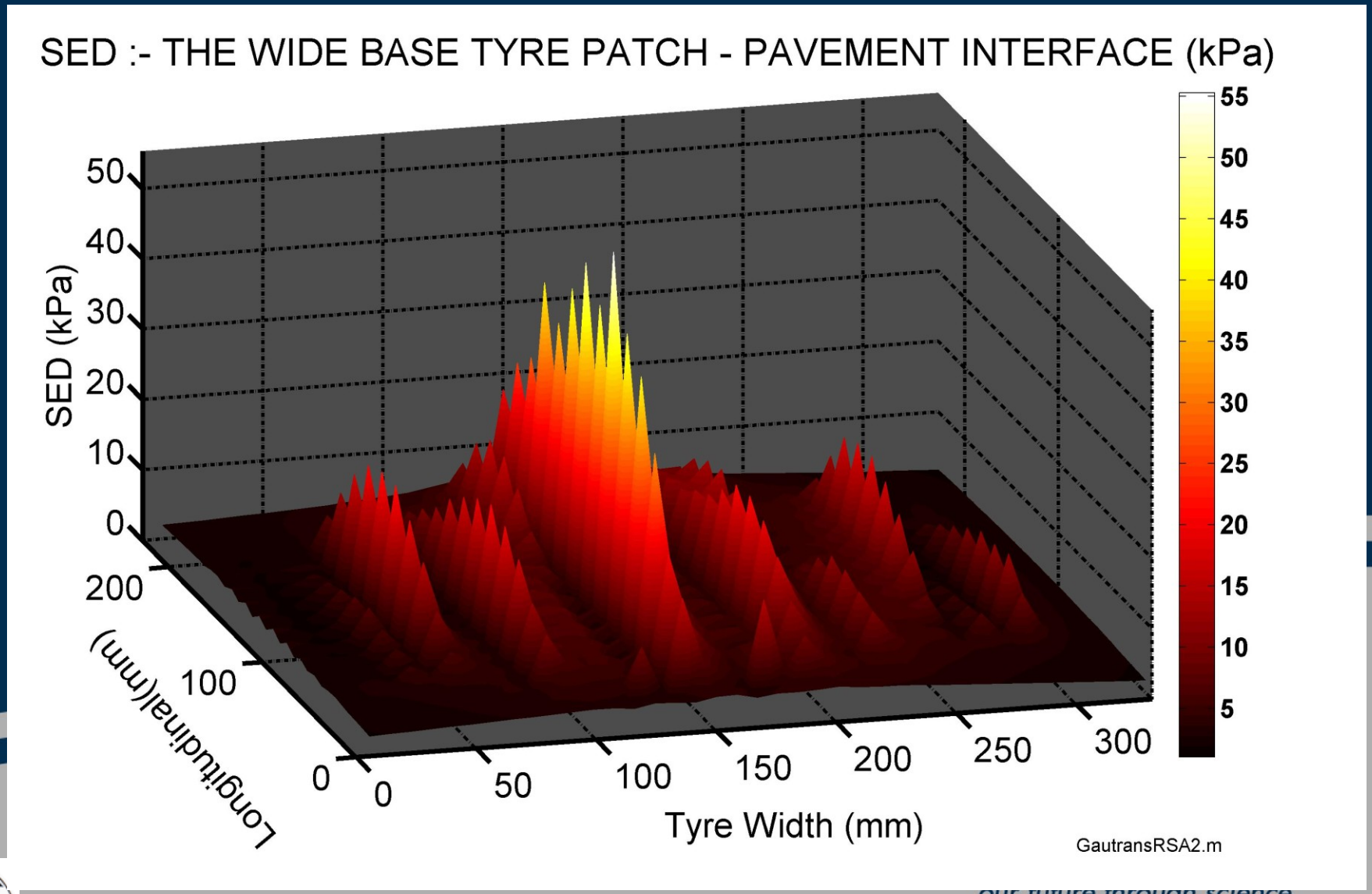

SED :- THE WIDE BASE TYRE PATCH - PAVEMENT INTERFACE (kPa)
SED (kPa)
50
40
30
20
10
0
200
100
0
Longitudinal(mm)
0
50
100
150
200
250
300
Tyre Width (mm)
55
50
45
40
35
30
25
20
15
10
5
GautransRSA2.m

Tyre Tested 12R22.5 (HP3000 P.R. 152/148L TREADED)

Inflation Pressure = 720 kPa

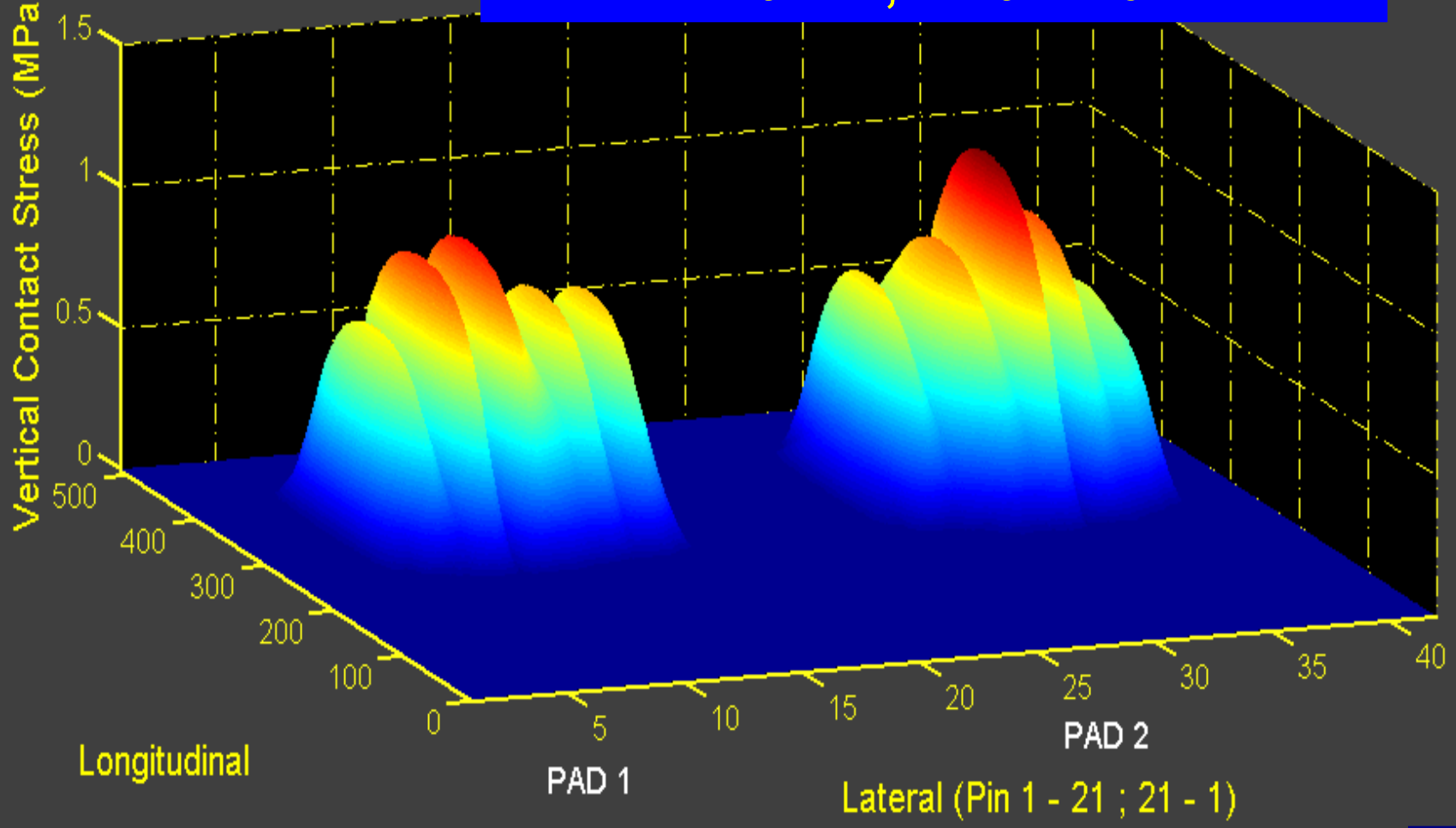
Measured Vertical Total Load = 40.4 kN

Applied Vertical Load (HVS

Wheel speed = 1.02 m/s

Max Stress = 1.15 MPa

STANDARD TYRE LOAD:
40 kN, 720 kPa



Filename : HVS091az (hvsdaul.m)

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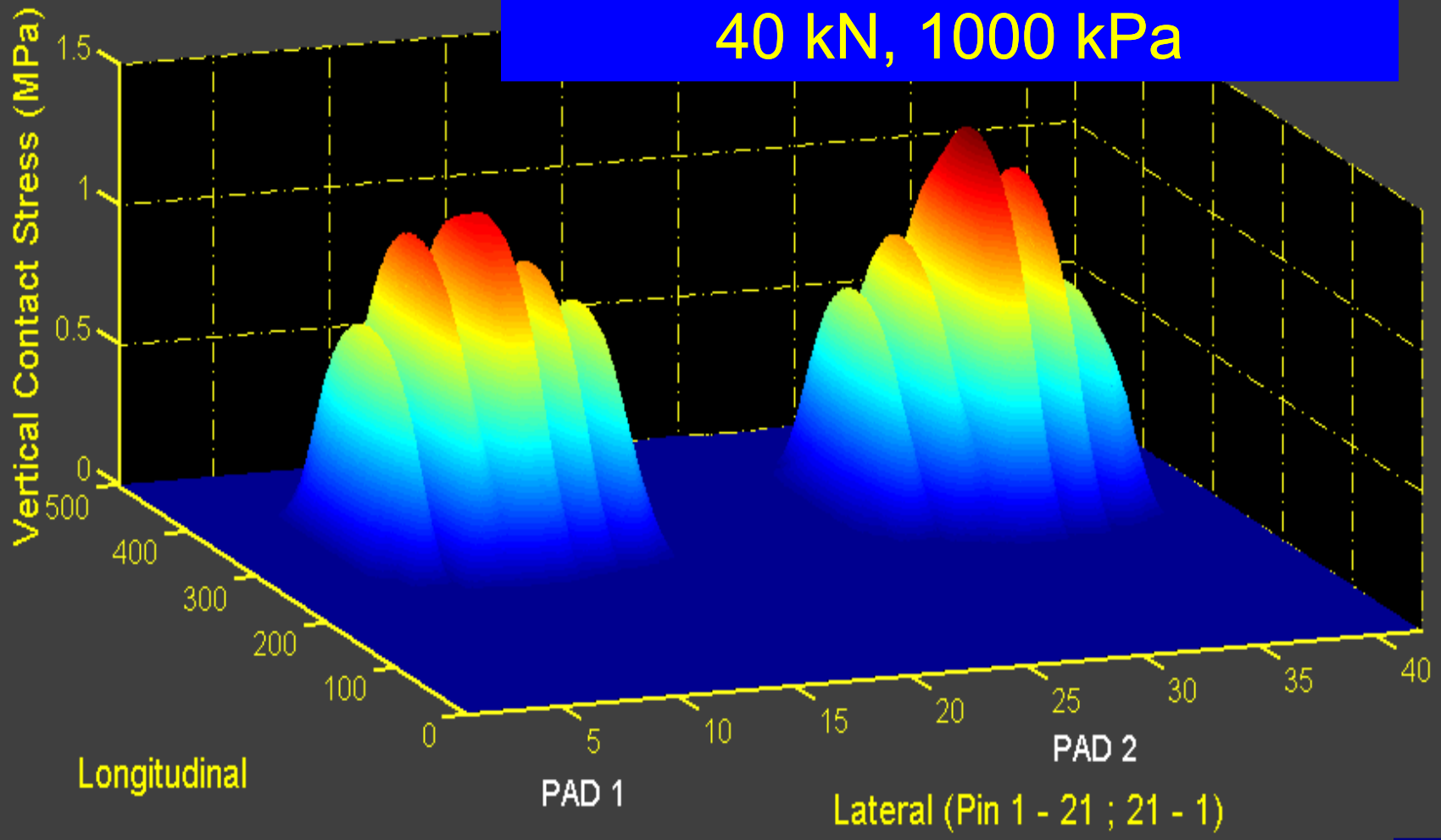
Tyre Tested 12R22.5 (HP3000 P.R. 152/148L TREADED)

Inflation Pressure = 1000 kPa
Applied Vertical Load (HVS) = 40.1 kN
Wheel speed = 1.02 m/s
Max Stress = 1.29 MPa

Measured Vertical Total Load = 37.8 kN
Measured Vertical Load (Pad 1) = 19.3 kN

STANDARD TYRE LOAD:
40 kN, 1000 kPa



Filename : HVS043az (hvsdaul.m)

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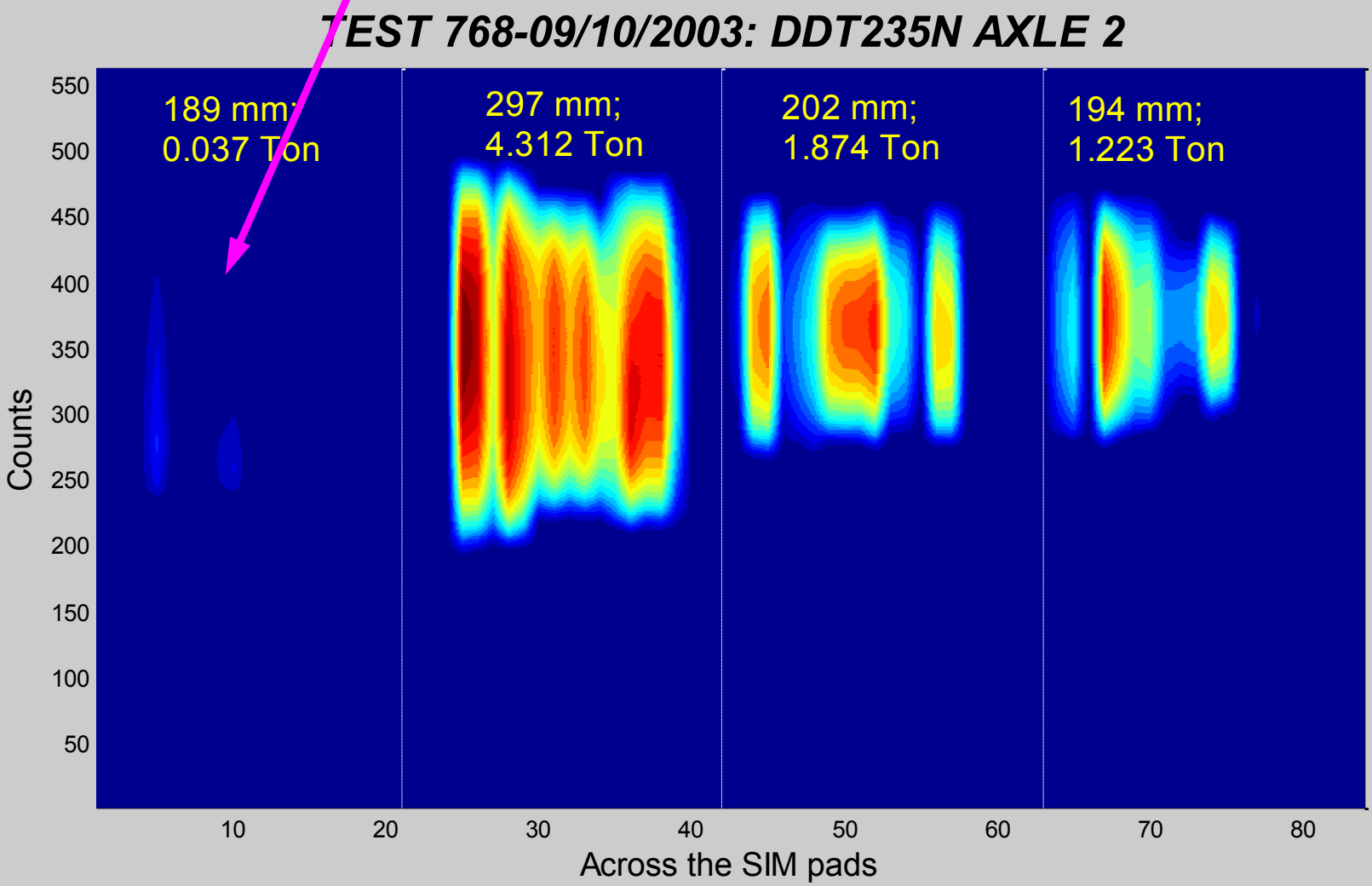
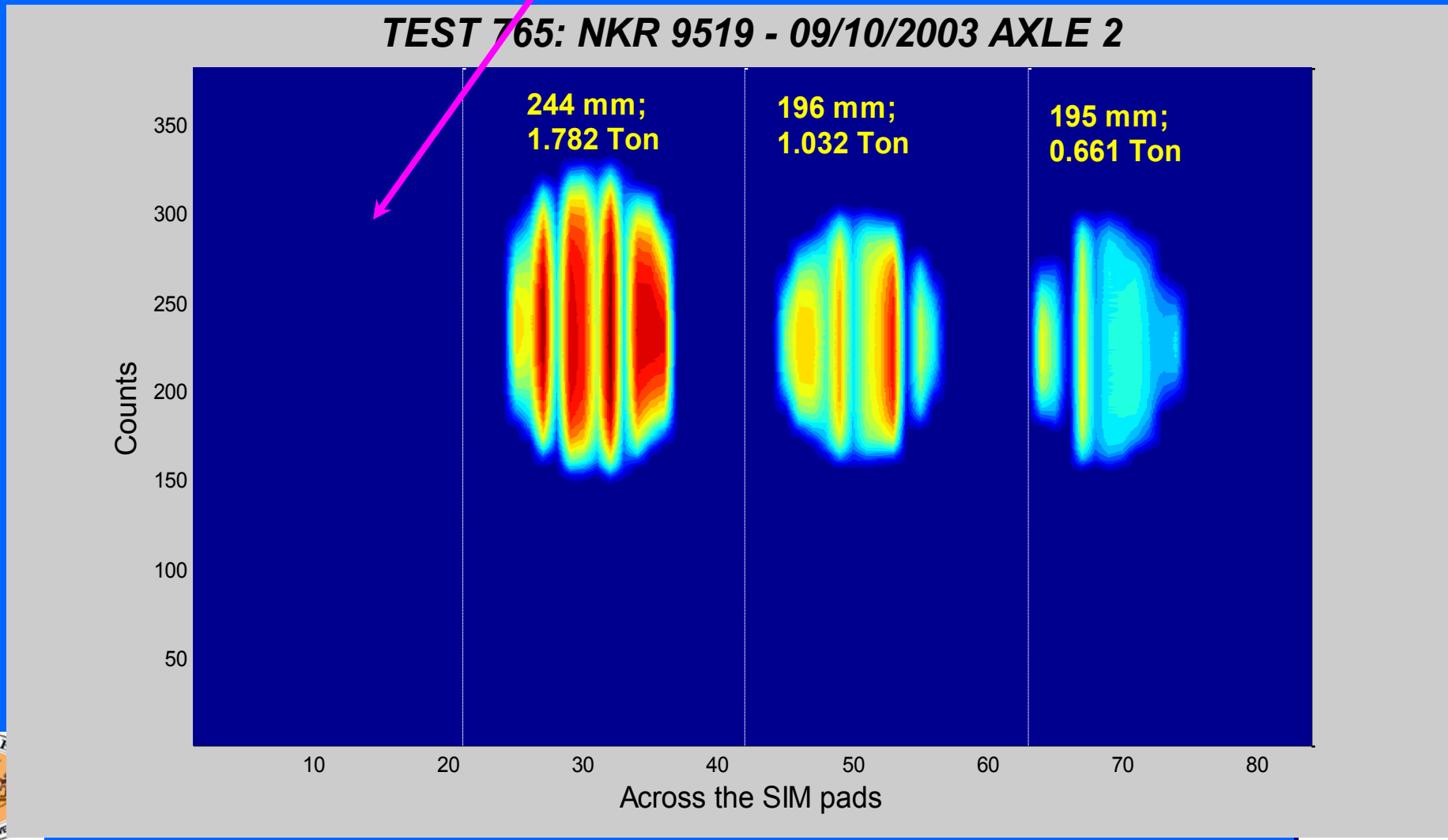
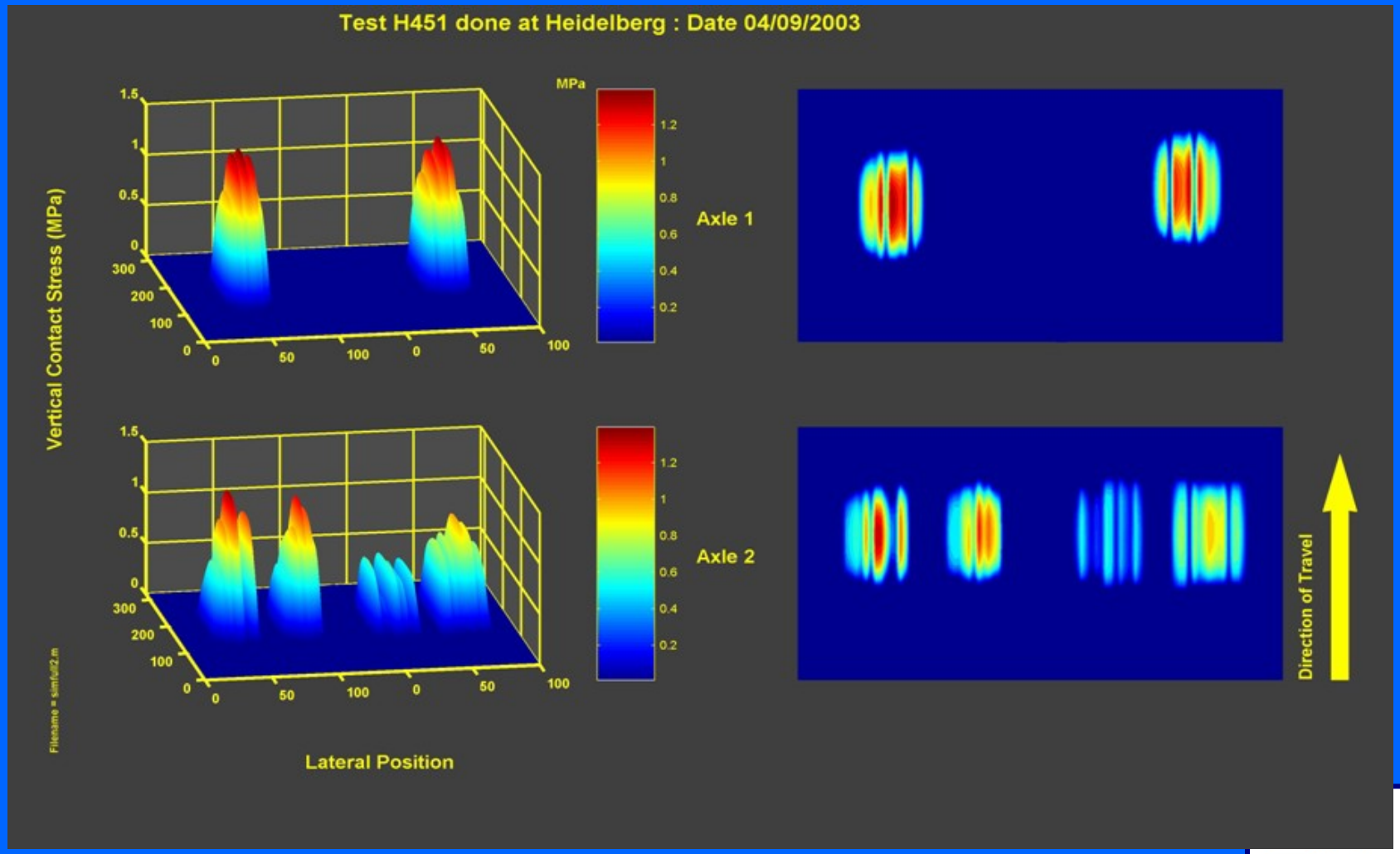
TYRE BARELY IN CONTACT WITH SURFACE



AXLE 2: MISSING TYRE !!



Two Axle Truck – Vertical Contact Stress - Foot Prints



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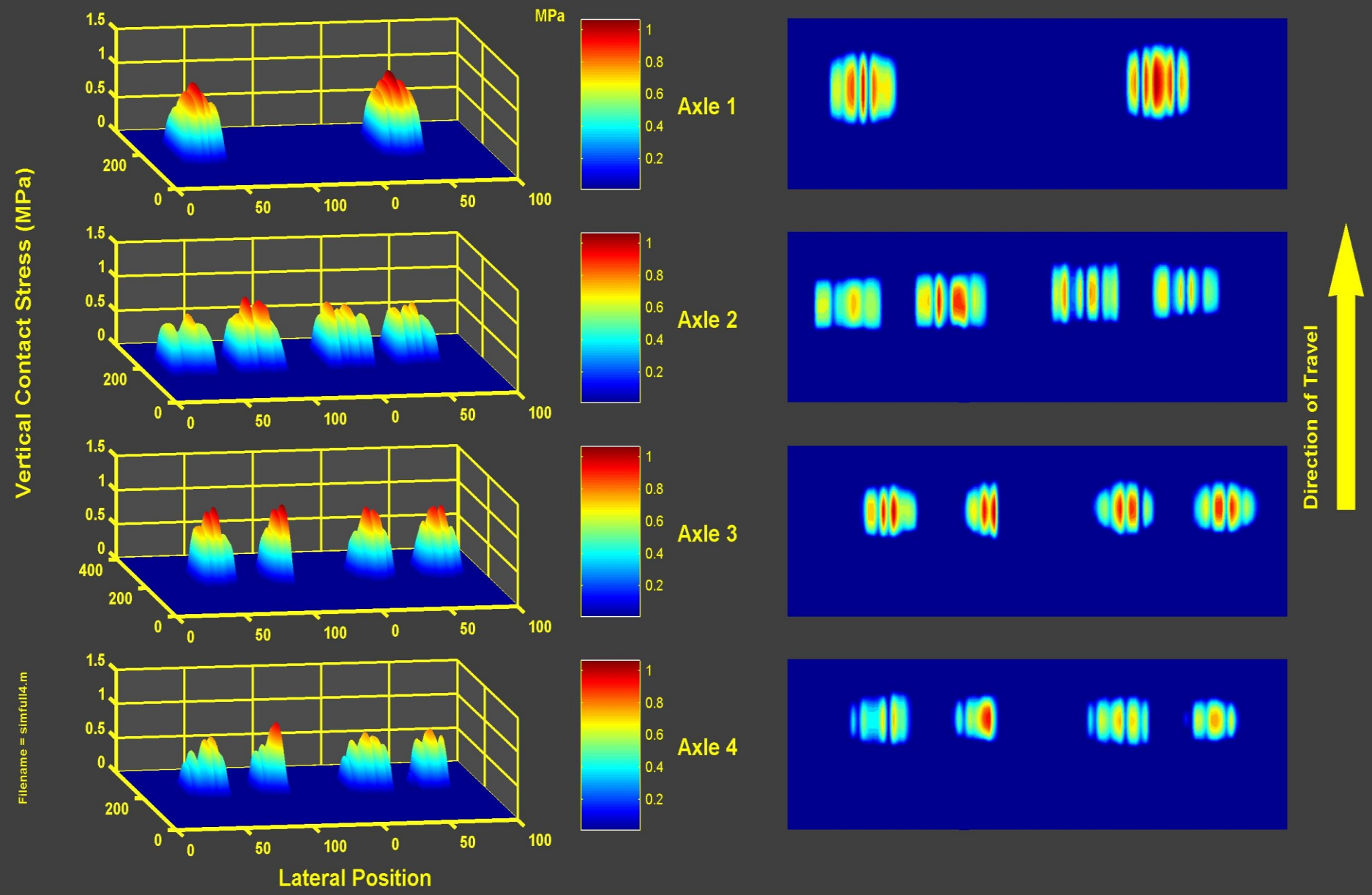
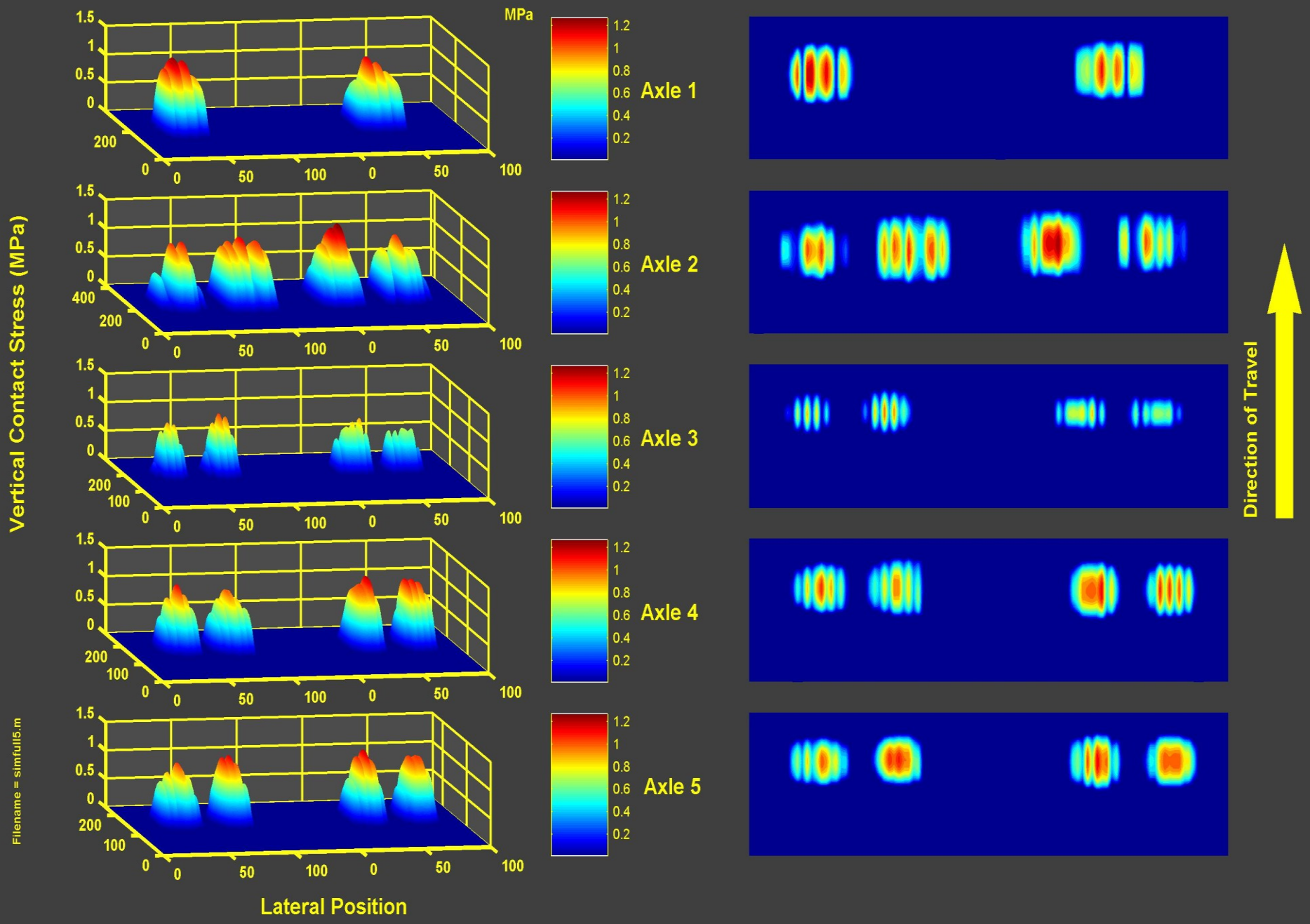
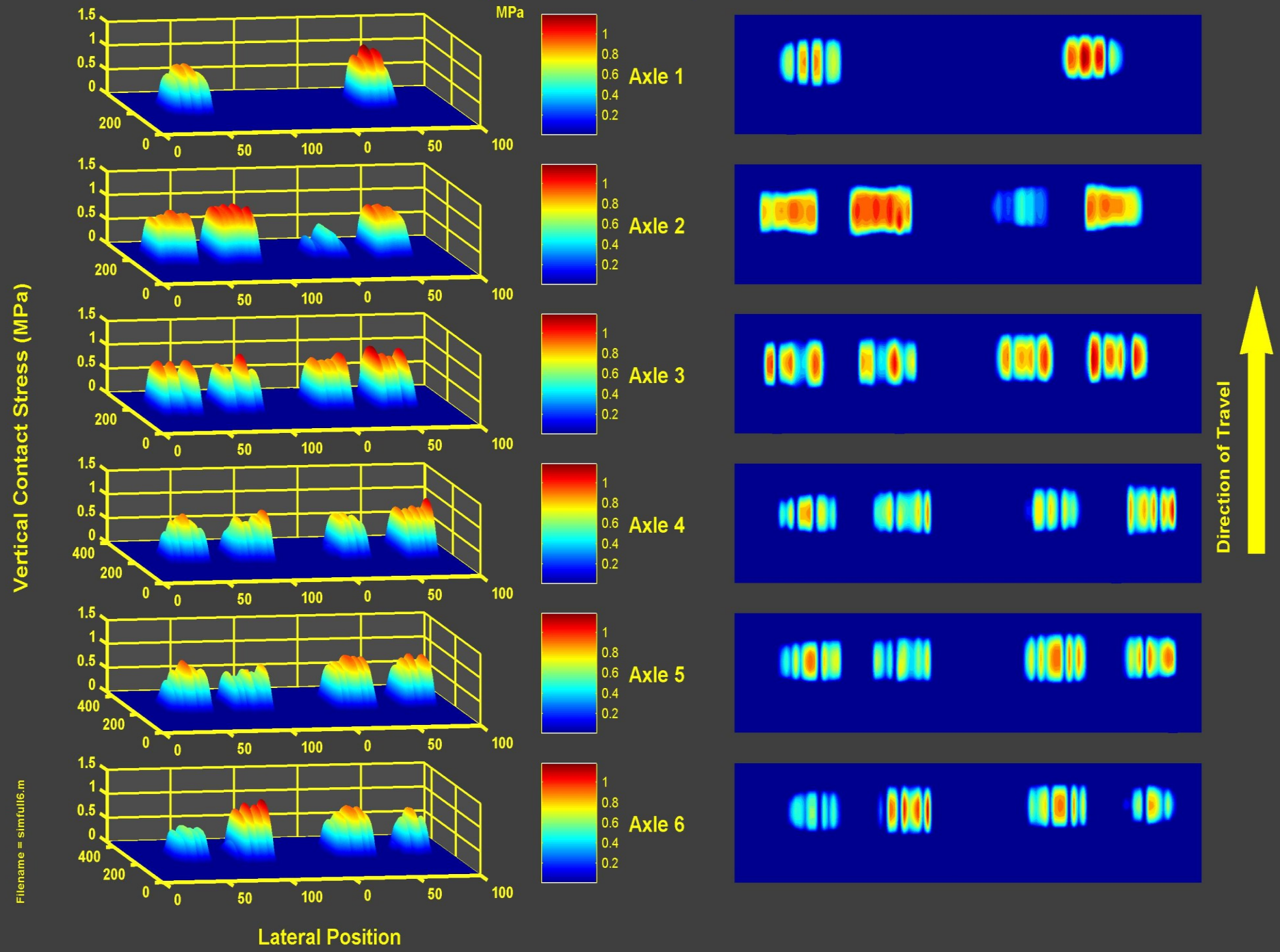
Test H1070 done at Heidelberg : Date 10/09/2003

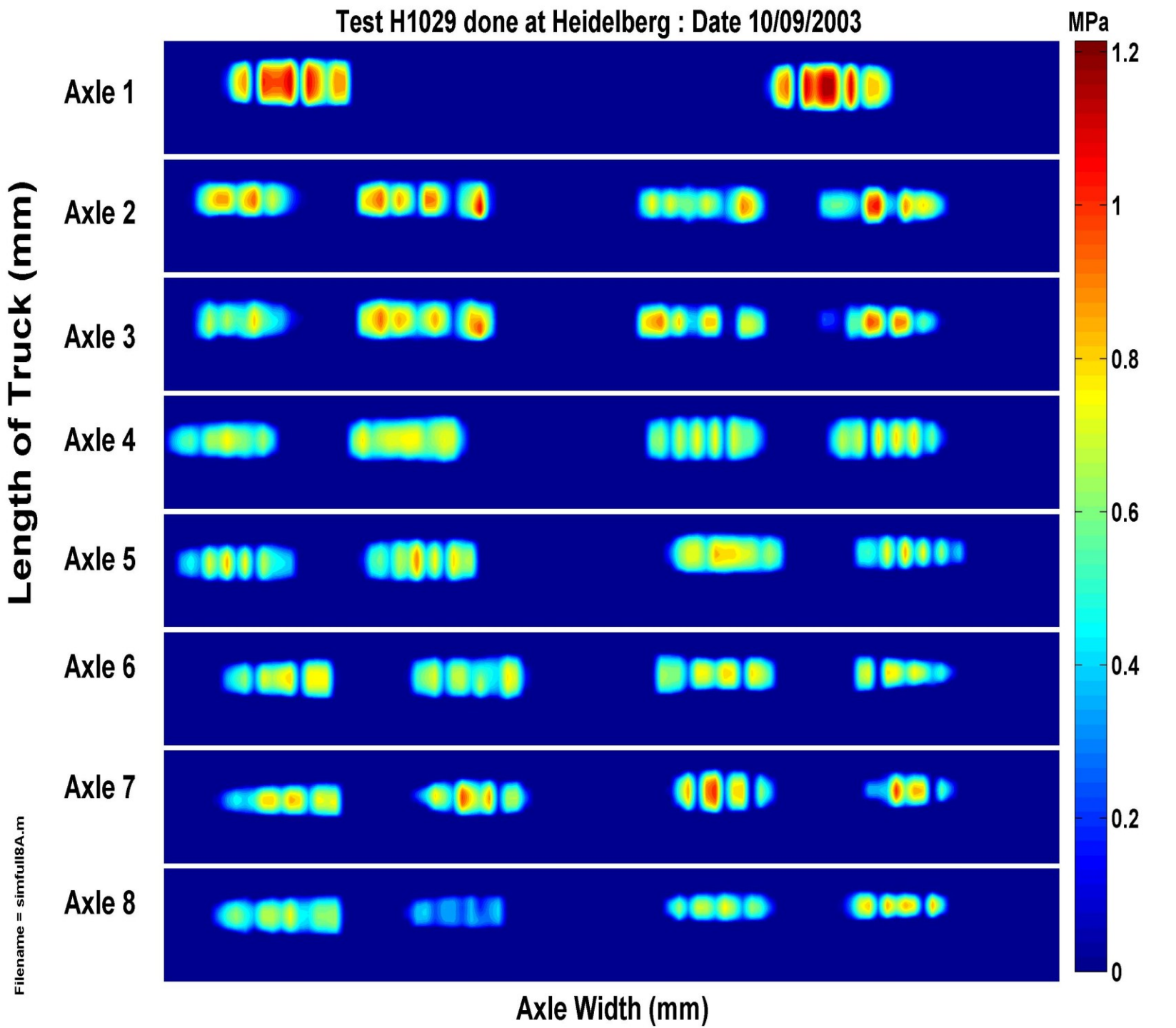


Test H1077 done at Heidelberg : Date 10/09/2003

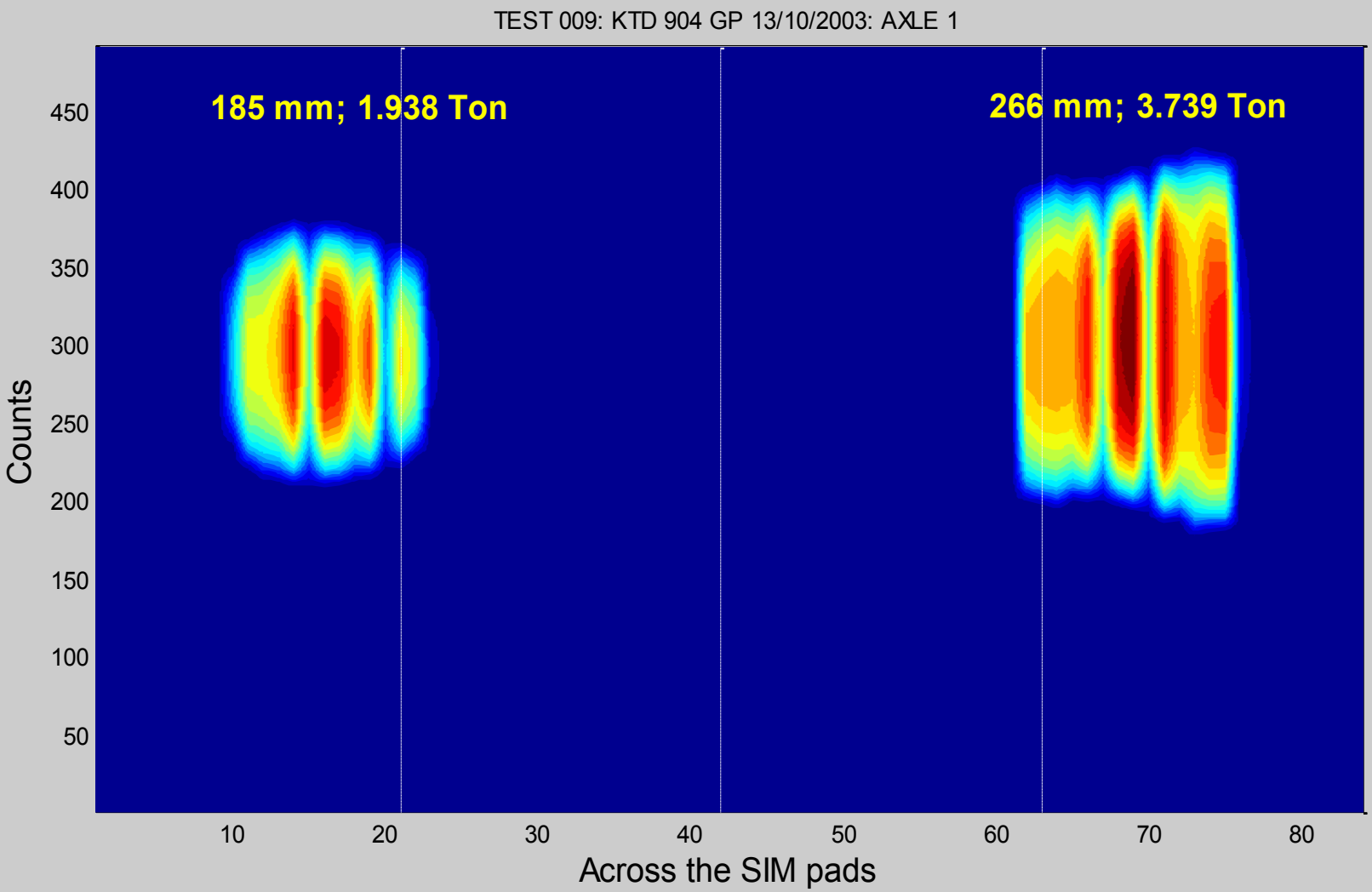


Test 174 done at Heidelberg : Date 10/09/2003 (overload)




Test H1029 done at Heidelberg : Date 10/09/2003
MPa
1.2
1
0.8
0.6
0.4
0.2
0
Axle 1
Axle 2
Axle 3
Axle 4
Axle 5
Axle 6
Axle 7
Axle 8
Length of Truck (mm)
Axle Width (mm)
Filename = simfull8A.m

STEERING AXLE – UNEQUAL LOADING



THE END

THANKS FOR ATTENTION

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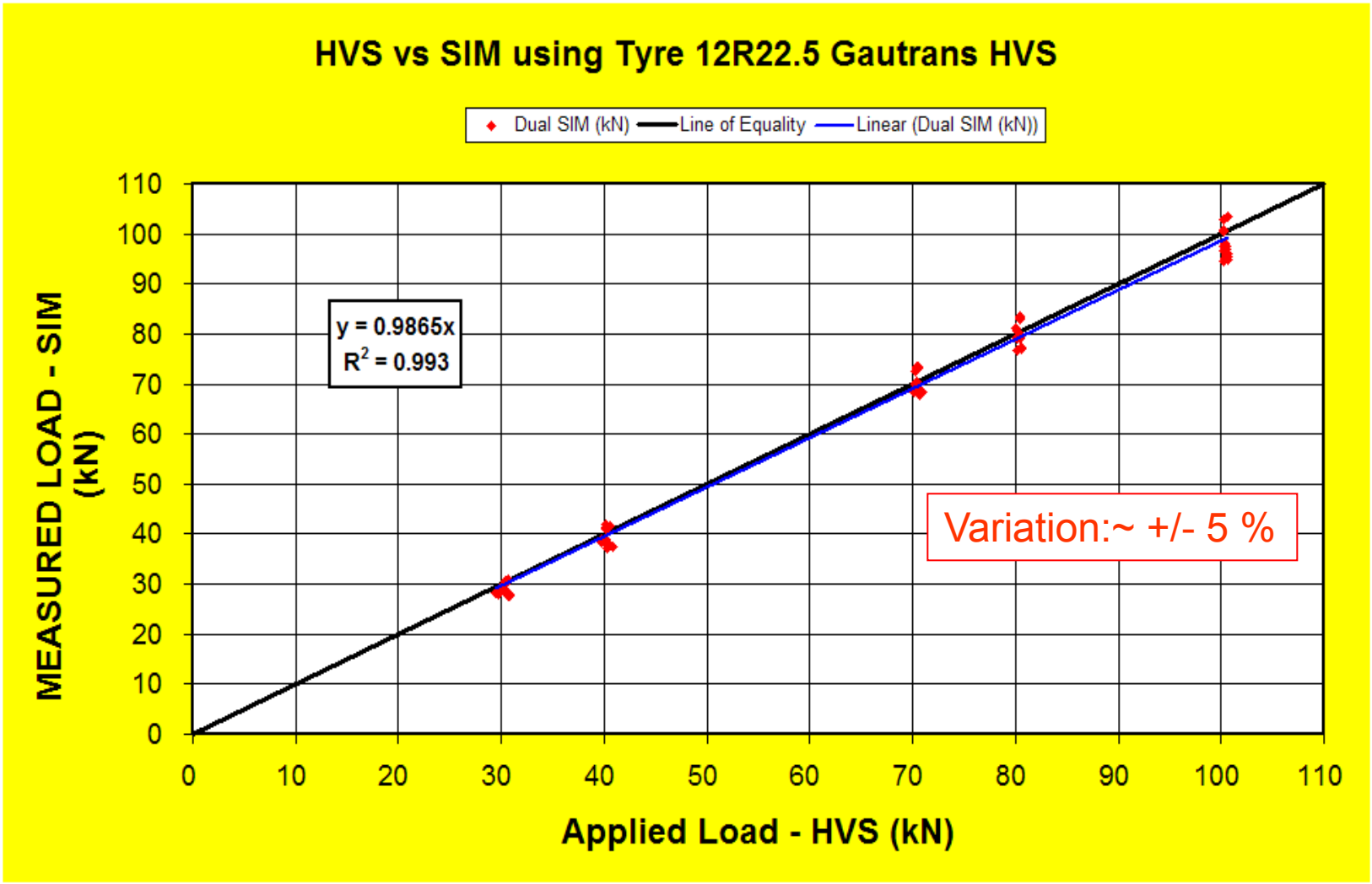
TYRE LOAD COMPARISON – HVS-SIM



September 2004 – 250 mm Concrete slab @ Gautrans- KoedoesPoort

Smooth Plates – HVS Dual Tyre Tests