APPENDIX A: DIMENSIONAL AND COMPONENT CHARACTERISTIC DATA USED IN VEHICLE SIMULATIONS

A.1. Introduction

An extract of the dimensional and component characteristic data are shown in this Appendix. These data were used for the vehicle simulations in this thesis. The objective of these simulations was to obtain realistic vehicular load histories for input to the pavement structures.

The data consist of dimensional data for the three typical vehicles used in the simulations and component characteristic data for the vehicle suspension and tyres. The complete data set is shown in the report by Gilliomee (1999).

The data shown in this appendix are referred to in Chapters 2.3.2 and 4.6.1 and used for the vehicle simulations described in Chapter 5.

A.2. Dimensional Data

The dimensional data used in the vehicle simulations were obtained from real vehicles. In Table A.1 the vital dimensions for each of the three vehicles / vehicle combinations are shown. Sketches of the three vehicles used in the simulations are shown in Figure A.1.

Table A.1: Dimensional data for three vehicles used in vehicle simulations (from Gilliomee, 1999).

PARAMETER	VEHICLE IDENTIFICATION AND DATA		
	Rigid (11)	**Articulated (123)**	**Interlink (1222)**
Length [m]	7,91	16,41	21,93
Width [m]	2,47	2,49	2,49
Height [m]	2,57	3,32	3,32
GVM/GCM [kg]	15 950	48 900	58 800

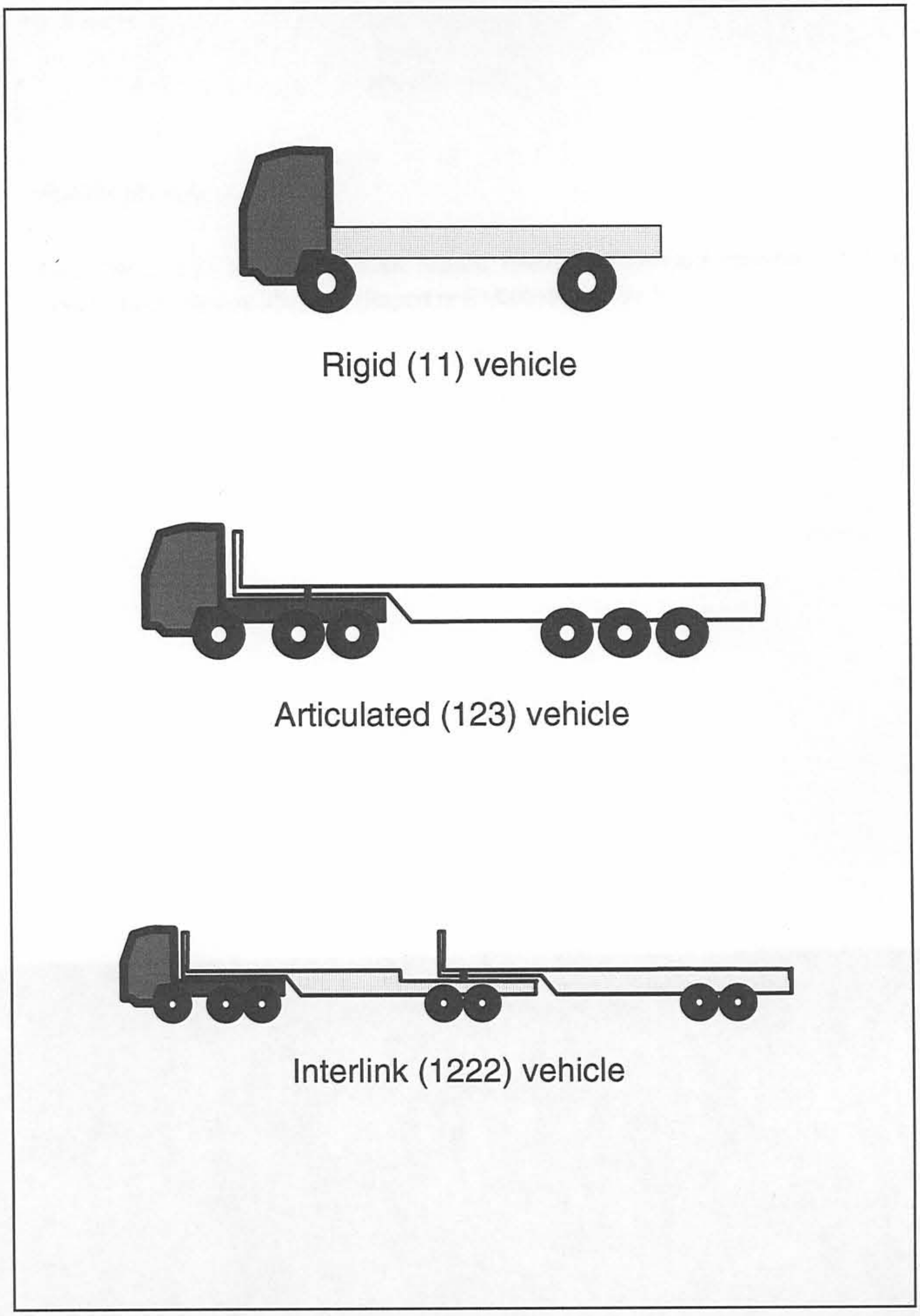


Figure A.1: Sketches of three vehicles used in tyre load simulations.

A.3. Component Characteristic Data

The components for which data were needed in the vehicle simulations are the tyres and suspension. This data were also obtained from actual tyres and suspension systems. The data used in the vehicle simulations are shown in Tables A.2 (tyre data) and A.3 (suspension data).

Table A.2: Tyre data used in vehicle simulations (from Gilliomee, 1999).

PARAMETER	DATA
Type and size	12 R22.5 duals
Tyre inflation pressures	Manufacturer recommended tyre inflation pressures were used for all loads.

Table A.3: Suspension data used in vehicle simulations (from Gilliomee, 1999).

PARAMETER	DATA
Type	Steel leaf spring
Spring deflection rate [kg/mm]	90

A.4. Observations

The following observation is made from the information in this appendix:

a. The data provided are actual vehicle component characteristic data obtained from a specific vehicle, and should specific vehicles be investigated, their data should be used instead of the data provided in this appendix.

A.5. References

GILLIOMEE, C.L. 1999. **Simulation report: Heavy vehicle load histories.** Pretoria: Land Mobility Technologies (Pty) Ltd, (Report nr R1/00015/1, Issue 1).

B. FREQUENCY DOMAIN ANALYSES FOR ESTABLISHING PAVEMENT ROUGHNESS UNIFORMITY

B.1. Introduction

The longitudinal pavement roughness data used for the vehicle simulations had to be uniform over the length of the test sections. Further, the three selected pavement sections had to be different from each other to ensure three different sets of load histories from the vehicle simulations. To ensure this uniformity and determine the differences between pavement sections Power Spectral Density (PSD) analyses were performed on the pavement profile data. The procedure used and main results are shown in this appendix.

The information in this appendix are referred to in Chapter 4.6.2 and used for the vehicle simulations in Chapter 5.

B.2. Pavement Profile Data

The pavement profile data used in the vehicle simulations were obtained from the High Speed Profilometer (HSP) (Kemp, 1997). This data consist of vertical pavement profiles for two wheeltracks 1,6 m apart at 245 mm intervals.

Three pavement sections were identified. They were initially selected based on their average pavement roughnesses in terms of IRI. As different pavement profiles can result in similar pavement roughnesses (Mann et al, 1997), the actual pavement profile data were analysed to ensure that the three profiles are different from each other and uniform over its lengths.

Basic information regarding these three pavement sections is shown in Table B.1. In Figure B.1 the pavement profiles (left and right wheeltracks) for the three pavement sections are shown.

Table B.1: Basic information regarding pavement sections used for vehicle simulations (from Kemp, 1999).

PARAMETER	VALUE OF PARAMETER		
Identification	Smooth (S)	Average (A)	Rough (R)
Length [km]	6,0	6,0	6,0
IRI [mm/m] L; R*	1,5; 1,5	3,9; 4,4	7,8; 5,5
HRI [mm/m]	1,2	3,1	5,3
TRRI [mm/m] L; R*	1,8; 1,8	4,8; 5,5	9,2; 6,6
HTRRI [mm/m]	1,5	3,9	6,3
Environment	Rural, flat		

* Left and Right wheeltracks

B.3. Spectral Analysis Procedure

B.3.1 Process

The spectral analysis performed on the pavement profile data consisted of two distinct phases. The first phase focussed on determining the uniformity of the pavement sections and the second phase on the difference between the three pavement sections.

The first phase consisted of the following steps:

a. Division of each pavement profile into six 1 km section lengths;
b. Performance of PSD analyses on each of the 1 km section lengths for each wheeltrack;
c. Performance of a PSD analysis on the whole pavement test section for each wheeltrack;
d. Comparison of the PSD output of each of the 1 km sections with each other using the ISO specification (ISO, 1995);
e. Comparison of the PSD outputs of the two wheeltracks (for the whole pavement test sections length) with each other, using the ISO specification (ISO, 1995);
f. Decision on the uniformity of the pavement test sections;
g. Classification of the whole pavement section according to ISO 8608 (ISO, 1995).

The second phase consisted of the following steps:

a. Use the PSD outputs calculated for each of the complete pavement sections as input data (both wheeltracks);
b. Comparison of the PSD outputs of each of the three pavement test sections with each other using the ISO specifications (ISO, 1995), and
c. Decision on the difference between the three pavement test sections.

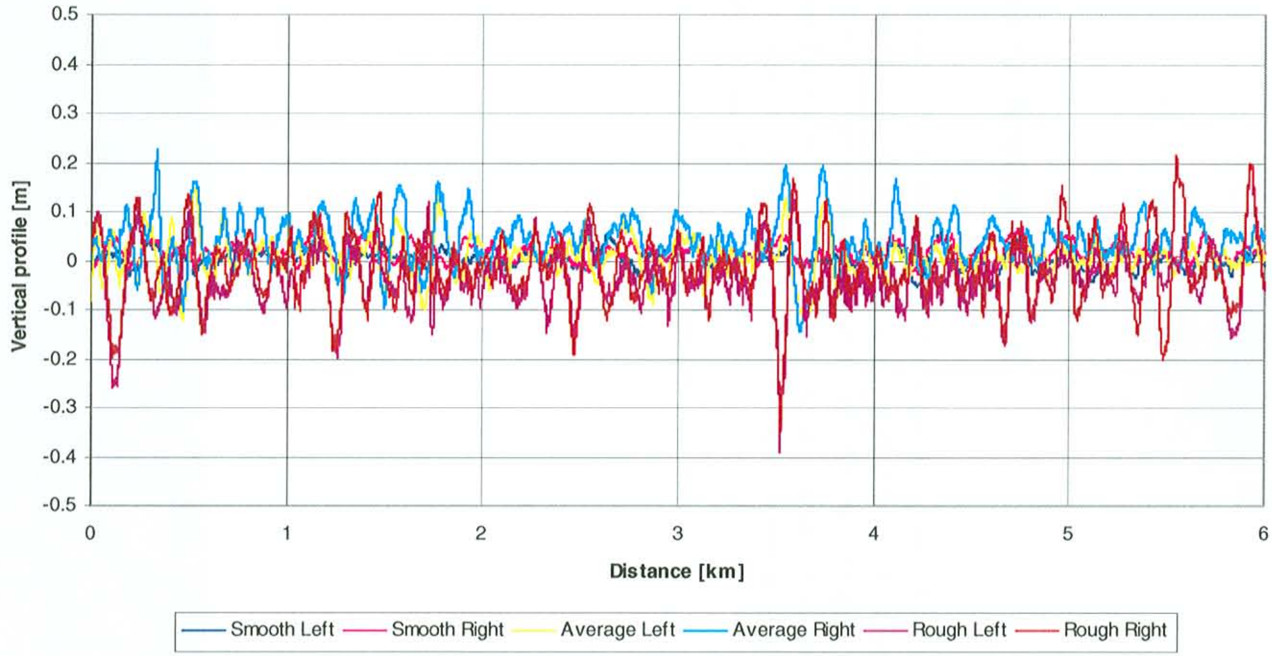


Figure B.1: **Pavement profiles of three selected pavement sections (left and right wheeltracks)**

B.3.2 Mathematical details of procedure

The PSDs in this thesis were all calculated using the MATLAB Version 5.11 (Mathworks, 1999) package with the Signal Processing Toolbox (Mathworks, 1999). In this section some of the Matlab-specific information is provided for background. This information is not essential for the understanding of the thesis.

The command used for the PSDs were:

psd = psd(section name,8 192, [], 1 024);

where section name refers to the actual set of pavement profile data used in the analysis (measured at 245 mm intervals with the HSP);
8 192 is the number of points used in the FFT;
[] indicates that the Hanning window was used;
1 024 is the length of the window used.

To plot the PSD the x-axis intervals were calculated using the following equation:

*Spatial Frequency [c/m] = (position # / FFT length) * (# of points in PSD / distance [m])*

The specific equation to obtain the x-axis data for the 6,0 km sections was

*x = (1 / 8 192) * (24 336/ 6 000) = 0,00049512*

The specific command to generate the x-axis data was:

t=[0:0,0004951:2,028;]';

The 2,028 parameter was calculated as follows:

*0,0004951 * 4 096 = 2,028.*

B.4. Spectral Analysis Output

The output from the various spectral analyses described in B.3 are summarised in Figures B.2 to B.8. Figures B.2 and B.3 consist of a summary of the PSD outputs of the smooth test section as calculated for 1 km intervals. Figures B.4 and B.5 show this data for the average test section and Figures B.6 and B.7 for the rough test section. Figure B.8 shows the PSD outputs of the three pavement test sections together. The ISO classifications for the three pavement test sections are shown in Table B.2.

Table B.2: ISO classification (ISO, 1995) for each test section.

PARAMETER	SECTION IDENTIFICATION AND DATA		
	Smooth	**Average**	**Rough**
1 km section data			
ISO classification	A	BC	BCD
Whole test section data			
ISO classification	A	BC	CD

Analysis of the data in Figures B.2 to B.7 indicates that the three test sections are relatively uniform over their respective lengths in terms of the ISO 8608 classification (ISO, 1995), and thus suitable for the purposes of the vehicle simulations in this thesis. The wheeltracks from each pavement section are also relatively uniform.

Analysis of the data in Figure B.8 indicates that the three pavement test sections are different from each other and thus suitable for the purposes of the vehicle simulations in this thesis. In Figure B.8 the frequency ranges over which the 3 speeds at which the vehicle simulations are done are indicated. This is done in terms of the approximate body bounce and axle hop frequencies. The profile data are specifically different over the 120 km/h and 80 km/h speed ranges, although some similarity occurs at the higher frequency end of the 40 km/h range for the Rough and Average pavement sections.

B.5. Conclusions

Based on the information in this Appendix, the following conclusions are drawn:

a. The three pavement test sections selected for vehicle simulations are uniform over their lengths in terms of the ISO 8608 classification;
b. The three pavement test sections selected for vehicle simulations are different in terms of the ISO 8608 classification over the speeds investigated, and
c. The three pavement test sections selected can be used for the vehicle simulations in this thesis.

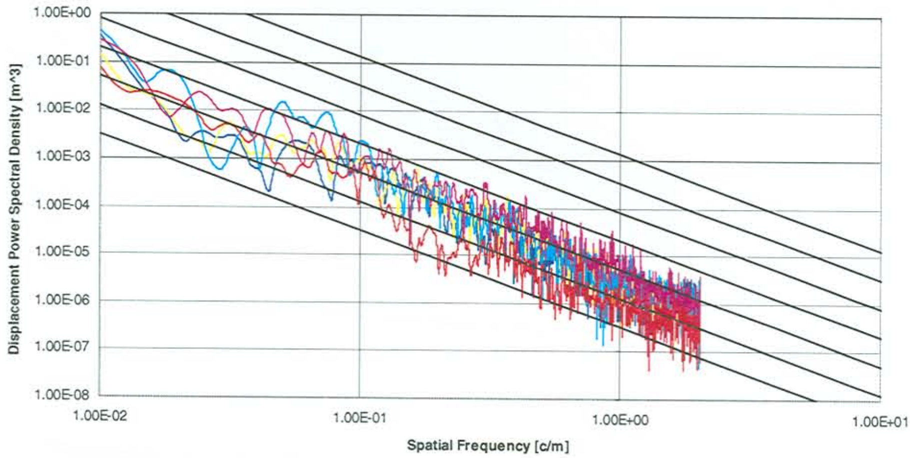


Figure B.2: **Displacement Power Spectral Density (PSD)-based ISO classification of Smooth pavement test section for left wheeltrack in 1,0 km sections.**

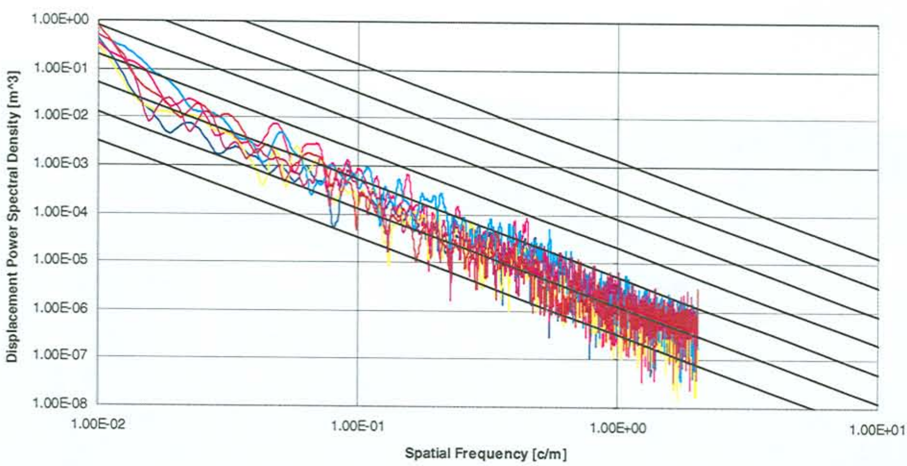


Figure B.3: **Displacement Power Spectral Density (PSD)-based ISO classification of Smooth pavement test section for right wheeltrack in 1,0 km sections.**

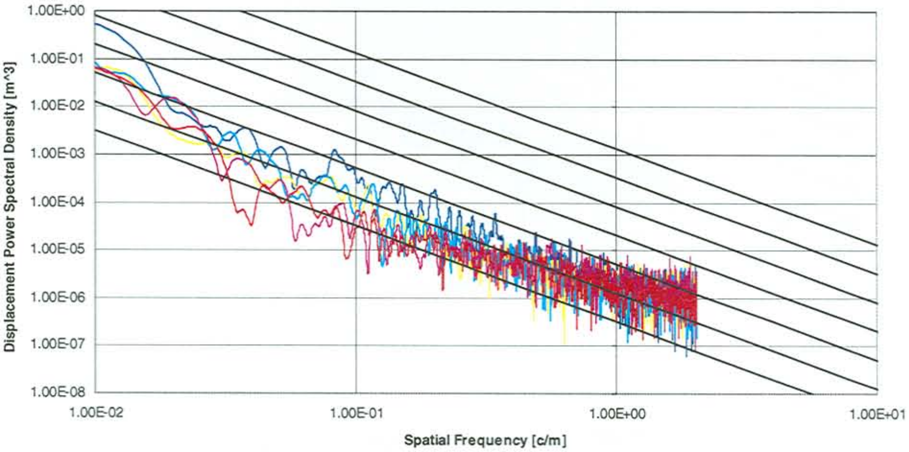


Figure B.4: **Displacement Power Spectral Density (PSD)-based ISO classification of Average pavement test section for left wheeltrack in 1,0 km sections.**

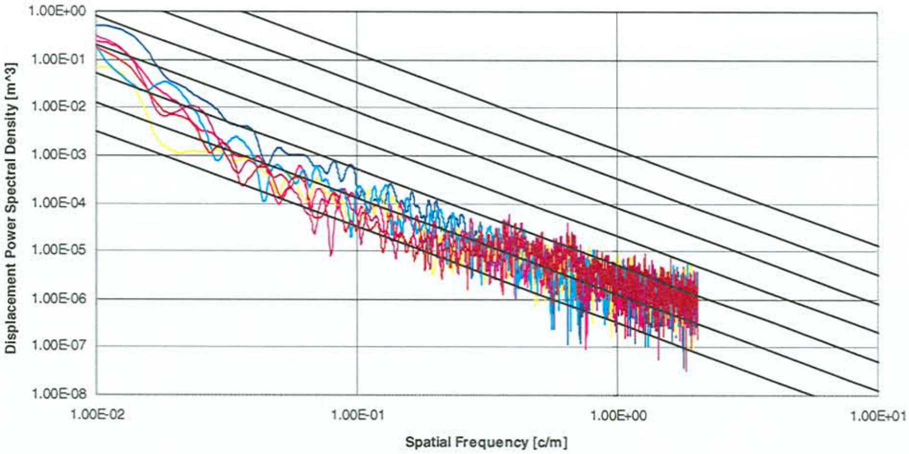


Figure B.5: **Displacement Power Spectral Density (PSD)-based ISO classification of Average pavement test section for right wheeltrack in 1,0 km sections.**

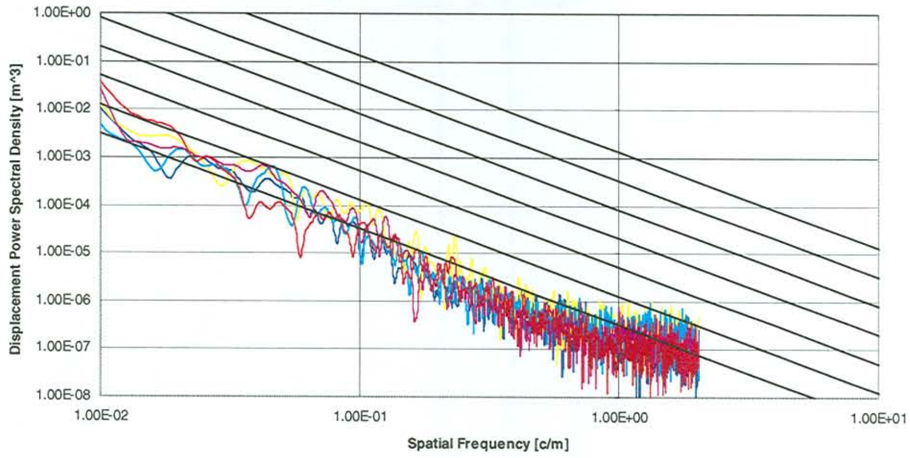


Figure B.6: **Displacement Power Spectral Density (PSD)-based ISO classification of Rough pavement test section for left wheeltrack in 1,0 km sections.**

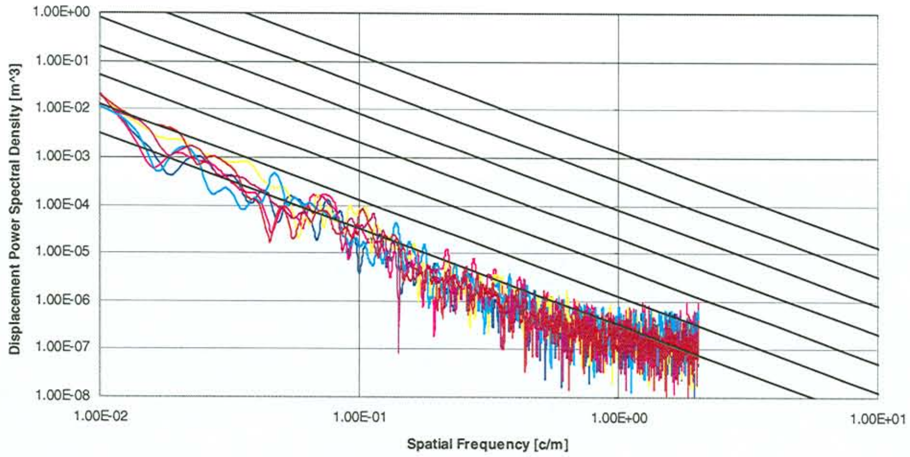


Figure B.7: Displacement Power Spectral Density (PSD)-based ISO classification of Rough pavement test section for right wheeltrack in 1,0 km sections.

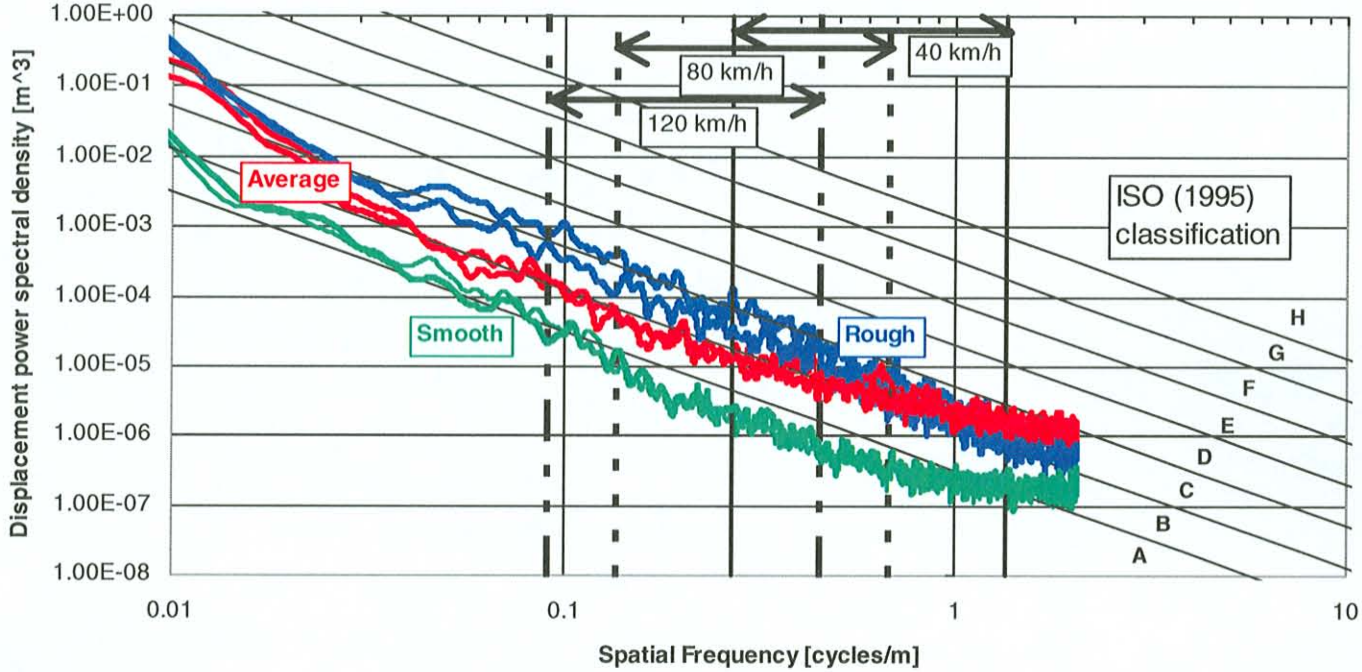


Figure B.8: **Displacement Power Spectral Density (PSD)-based ISO classification of all three pavements.**

B.6. References

International Organisation for Standardization. 1995. **Mechanical vibration - Road surface profiles - Reporting of measured data.** Genève: ISO. (ISO 8608: 1995(E)).

KEMP, M. 1997. **Personal communication on surface roughness measurement and analysis.** Pretoria: CSIR, Project leader.

KEMP, M. 1999. **Personal communication on HSP pavement profile data.** Pretoria: CSIR, Project leader.

MANN, A.V., McMANUS, A.M. and HOLDEN, J.C. 1997. **Power spectral density analysis of road profiles for road defect assessment.** Road and Transport Research, Volume 6, Number 3. pp 36-47.

The MathWorks Inc. 1999. **MATLAB, the language of technical computing.** Natick, MA. (Release 11).

APPENDIX C: DATA ON THE TYRE LOADS FROM STATIC AND DYNAMIC SOURCES

C.1. Introduction

The procedures used to analyse the tyre load data are described in this appendix. All the analyses procedures in this appendix relate to data and discussions in Chapter 5. The objective of this appendix is to provide background to the procedures used in Chapter 5.

C.2. Data Characterisation

The statistics (average, standard deviation, maximum, minimum, 95th, 90th, 80th, 50th and 25th percentiles, skewness, kurtosis, variance and Dynamic Load Coefficient (DLC)) for each set of data were calculated. This was done in such a way that:

- A set of data for each vehicle at all the speeds, loads and roughnesses;
- A set for each speed for all the vehicles, roughnesses and loads;
- A set for each load for all the vehicles, speeds and roughnesses, and
- A set for each roughness for all the vehicles, speeds and loads

were calculated.

The rationale was that the effect of all the parameters on each of the other parameters are more important in a practical situation where for instance all the vehicles will travel at the selected speeds, being loaded at various loads and on various roughnesses, than the effect of one specific vehicle at a specific speed and load on a specific roughness. The thesis focuses on a phenomenological and practical approach.

The data from the various tyre load analyses were used to determine whether statistically significant relationships exist between the wheel loads on the various axles, as well as between the wheel loads calculated using the static, intermediate (TFP) and complicated (DADS) analyses. These data were analysed for the following relationships:

- Single, tandem and tridem axle data;
- Steer, drive and trail data;
- Left and right hand side of the DADS data (TFP assumes similar data on the two sides of the vehicle);
- All DADS and all TFP data, and
- 11, 123 and 1222 vehicle data.

The results of the statistical analyses are shown in Tables 5.1, 5.2, and 5.3 (for all the tyre data together) and tables C.1 to C.9 (for each of the steer, drive and trail wheel sets of data). In these tables it is important to observe that the smallest wheel load allowed in the TFP simulation is 0.0, and therefore this would be the minimum load whenever the wheel loses contact with the pavement surface. In the DADS simulation a negative wheel load is calculated in such cases.

The data were analysed to determine the spectral content of the wheel loads. This was done using various options in the Matlab (Mathworks, 1999) environment. The objective was to determine the dominant axle hop and body bounce frequencies for each of the cases investigated. This analysis was only performed on the DADS data, as this is the only simulation where the wheel loads for each wheel was calculated. In the TFP simulation only one half of the vehicle was simulated.

A very high Power Spectral Density (PSD) value was observed in each of the cases for very long wavelengths (more than 100 m). This correlated with load frequencies of between 0,1 and 0,3 Hz at speeds of 40 and 100 km/h. Analysis of a set of static data (moving constant load) indicated that the PSD value at these very high wavelengths corresponds to the static portion of the tyre loads (Figure C.1).

The area underneath a PSD curve can be calculated as an indication of the energy content of a specific frequency band. In this thesis the tyre loads were filtered to focus on the axle hop (> 10 Hz), body bounce (1 – 10 Hz), dynamic component (> 1 Hz) and ultra low (< 1 Hz) frequency bands. An elliptical filter was used for these analyses. Typical PSD curves indicating the four different frequency bands for a tyre load data set are shown in Figure C.2.

C.3. References

The MathWorks Inc. 1999. **MATLAB, the language of technical computing.** Natick, MA. (Release 11).

Table C.1: Summary of statistics for static tyre load data – STEER tyre.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (222)	Unladen	Laden	10 % Overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE LOAD PER WHEEL [kN]	28,4	31,2	30,8	22,2	33,2	35,0	Not applicable due to static loads			Not applicable due to static loads		
STANDARD DEVIATION [kN]	6,5	6,5	5,5	1,7	1,4	1,2						
COEFFICIENT OF VARIATION [%]	22,9	20,8	17,9	7,7	4,2	3,4						
MAXIMUM [kN]	33,6	36,3	35,1	23,6	34,5	36,3						
MINIMUM [kN]	20,1	22,9	23,6	20,1	31,6	33,6						
RANGE [kN]	13,4	13,4	11,4	3,5	3,0	2,7						
25 PERCENTILE	23,0	25,8	26,1	20,8	32,1	34,0						
50 PERCENTILE	31,6	34,5	33,6	22,9	33,6	35,1						
80 PERCENTILE	33,6	36,3	35,1	23,6	34,5	36,3						
90 PERCENTILE	33,6	36,3	35,1	23,6	34,5	36,3						
95 PERCENTILE	33,6	36,3	35,1	23,6	34,5	36,3						
# OF POINTS	6	6	6	6	6	6						
SAMPLE VARIANCE	42,1 mil[1]	42,3mil	30,8 mil	2,7 mil	1,8 mil	1,4 mil						
KURTOSIS	-1,9	-1,9	-1,9	-1,9	-1,9	-1,9						
SKEWNESS	-0,9	-0,9	-0,9	-0,8	-0,5	-0,1						

1 Million

Table C.2: Summary of statistics for static tyre load data – DRIVE tyre.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	Unladen	Laden	10 % Overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE LOAD PER WHEEL [kN]	18,8	17,5	16,9	7,5	21,5	23,7	Not applicable due to static loads			Not applicable due to static loads		
STANDARD DEVIATION [kN]	8,8	7,6	6,5	0,5	1,0	1,5						
COEFFICIENT OF VARIATION [%]	46,8	43,4	38,5	6,7	4,7	6,3						
MAXIMUM [kN]	26,3	23,8	22,3	8,1	23,1	26,3						
MINIMUM [kN]	7,0	7,1	8,1	7,0	20,4	22,3						
RANGE [kN]	19,3	16,7	14,2	1,0	2,7	4,0						
25 PERCENTILE	7,0	7,1	8,1	7,1	20,4	22,3						
50 PERCENTILE	23,1	21,6	20,4	7,1	21,6	23,8						
80 PERCENTILE	26,3	23,8	22,3	8,1	21,9	24,3						
90 PERCENTILE	26,3	23,8	22,3	8,1	23,1	26,3						
95 PERCENTILE	26,3	23,8	22,3	8,1	23,1	26,3						
# OF POINTS	12	24	24	20	20	20						
SAMPLE VARIANCE	77,6 mil2	57,3 mil	41,7 mil	0,2 mil	1,1 mil	2,2 mil						
KURTOSIS	-1,7	-1,6	-1,6	-2,0	-0,9	-0,6						
SKEWNESS	-0,7	-0,7	-0,7	0,4	0,6	0,8						

1 Million

Table C.3: Summary of statistics for static tyre load data – TRAILING tyre.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	Unladen	Laden	10 % Overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE LOAD PER WHEEL [kN]	No trailing tyre on Rigid (11) vehicle	15,2	16,8	5,1	20,4	22,8	Not applicable due to static loads			Not applicable due to static loads		
STANDARD DEVIATION [kN]		7,6	8,2	0,4	1,2	1,3						
COEFFICIENT OF VARIATION [%]		50,0	48,8	7,8	5,9	5,7						
MAXIMUM [kN]		22,6	24,4	5,6	21,9	24,4						
MINIMUM [kN]		4,3	5,2	4,3	18,4	20,5						
RANGE [kN]		18,3	19,2	1,3	3,5	3,9						
25 PERCENTILE		5,0	5,6	4,6	19,3	21,6						
50 PERCENTILE		19,3	21,4	5,2	20,3	22,7						
80 PERCENTILE		21,6	23,8	5,3	21,6	24,1						
90 PERCENTILE		22,1	24,1	5,6	21,9	24,4						
95 PERCENTILE		22,6	24,4	5,6	21,9	24,4						
# OF POINTS		36	48	28	28	28						
SAMPLE VARIANCE		58,4 mil3	68,0 mil	0,2 mil	1,4 mil	1,8 mil						
KURTOSIS		-1,5	-1,5	-0,8	-1,0	-1,1						
SKEWNESS		-0,7	-0,7	-0,5	-0,4	-0,4						

1 Million

Table C.4: **Summary of statistics for TFP-based tyre load data - STEERING tyre.**

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	Unladen	Laden	10 % Overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE WHEEL LOAD [kN]	28,4	32,1	Not applicable due to TFP inability to analyse 1222 vehicles	21,4	38,9	41,6	34,2	34,6	34,9	25,8	32,0	33,0
STANDARD DEVIATION [kN]	6,2	9,0		4,7	6,5	7,4	9,9	11,3	11,5	6,7	7,6	7,9
COEFFICIENT OF VARIATION [%]	21,8	28,1		21,7	16,7	17,8	29,1	32,5	32,9	26,0	23,9	23,9
MAXIMUM [kN]	46,0	78,4		49,0	69,0	78,4	52,8	78,4	65,9	49,0	69,0	78,4
MINIMUM [kN]	7,6	0,0		0,0	0,2	0,0	12,7	0,0	0,0	0,0	0,2	0,0
RANGE [kN]	38,4	78,4		49,0	68,8	78,4	40,1	78,4	65,9	49,0	68,8	78,4
25 PERCENTILE	21,0	24,4		19,5	34,9	36,7	22,9	23,2	23,0	20,7	29,3	30,0
50 PERCENTILE	31,2	34,3		20,9	40,1	43,0	36,0	36,3	36,9	24,5	33,2	34,1
80 PERCENTILE	33,6	38,0		23,5	43,6	47,5	43,9	45,0	46,0	32,6	36,4	37,9
90 PERCENTILE	34,6	41,0		25,6	45,0	48,8	46,8	47,4	48,3	33,7	38,9	40,1
95 PERCENTILE	35,5	45,3		29,0	46,9	50,6	47,7	49,3	51,0	34,5	43,5	44,0
# OF POINTS	19 296	21 436		12 074	13 878	13 878	8 136	13 308	19 287	12 074	12 976	13 878
SAMPLE VARIANCE	38,4 mil4	81,2 mil		21,6 mil	42,1 mil	54,7 mil	98,6 mil	126,9 mil	131,7 mil	45,2 mil	58,4 mil	62,2 mil
KURTOSIS	-1,3	1,1		7,0	3,4	2,3	-1,3	-0,6	-1,1	0,4	1,5	1,7
SKEWNESS	-0,5	-0,1		0,6	-0,8	-0,8	-0,2	-0,3	-0,2	-0,4	0,1	0,0
DLC	0,07	0,04		0,04	0,03	0,03	0,05	0,05	0,05	0,04	0,04	0,04

1 Million

Table C.5: Summary of statistics for TFP-based tyre load data – DRIVING tyre.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	Unladen	Laden	10 % Overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE LOAD [kN]	18,9	18,0	Not applicable due to TFP inability to analyse Interlink (1222) vehicles	7,1	27,2	30,2	21,8	22,4	23,0	11,4	20,9	22,2
STANDARD DEVIATION [kN]	8,6	8,1		2,5	9,1	10,7	13,3	12,9	14,1	8,0	6,5	6,1
COEFFICIENT OF VARIATION [%]	45,7	45,2		34,9	33,4	35,3	60,1	57,6	61,5	69,7	30,8	27,7
MAXIMUM [kN]	45,3	49,3		25,7	51,6	59,8	50,5	55,5	59,8	28,4	49,3	48,4
MINIMUM [kN]	0,0	0,0		0,0	0,0	0,0	0,5	0,0	0,0	0,0	0,0	0,0
RANGE [kN]	45,3	49,3		25,7	51,6	59,8	50,0	55,5	59,8	28,4	49,3	48,4
25 PERCENTILE	8,0	8,4		6,1	20,9	23,0	7,8	9,2	8,1	6,6	19,7	21,8
50 PERCENTILE	23,3	21,1		7,1	22,5	24,6	21,8	21,6	22,2	7,6	21,7	23,5
80 PERCENTILE	26,1	23,9		8,4	39,3	45,0	39,0	37,5	39,7	23,1	25,0	25,6
90 PERCENTILE	26,9	25,7		9,6	40,3	46,1	44,0	42,9	43,5	25,7	27,0	27,2
95 PERCENTILE	27,5	28,2		11,0	41,4	47,2	45,6	45,6	45,7	26,4	29,0	29,0
# OF POINTS	19 296	42 872		17 716	21 324	21 324	12 204	20 524	29 439	17 716	19 520	21 324
SAMPLE VARIANCE	74,4 mil5	66,0 mil		6,1 mil	82,8 mil	113,6 mil	172,5 mil	166,3 mil	199,5 mil	63,2 mil	41,6 mil	37,6 mil
KURTOSIS	-1,4	-0,7		4,8	-1,1	-1,1	-0,9	-0,8	-1,2	-0,6	1,6	2,4
SKEWNESS	-0,6	-0,3		0,6	0,5	0,6	0,5	0,4	0,3	1,0	-0,6	-1,4
DLC	0,15	0,06		0,06	0,06	0,06	0,10	0,10	0,10	0,12	0,05	0,05

1 Million

Table C.6: Summary of statistics for TFP-based tyre load data – TRAILING tyre.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	Unladen	Laden	10 % Overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE LOAD [kN]	Not Applicable	15,7	Not applicable due to TFP inability to analyse 1222 vehicles	4,6	19,7	21,5	15,1	16,6	17,3	4,6	19,7	21,5
STANDARD DEVIATION [kN]		7,8		2,0	3,3	2,1	7,6	7,8	10,7	2,0	3,5	2,1
COEFFICIENT OF VARIATION [%]		49,8		43,3	16,8	9,9	49,9	47,3	61,9	43,6	17,8	9,9
MAXIMUM [kN]		46,1		17,4	46,1	33,3	26,5	46,1	46,8	17,4	46,1	33,3
MINIMUM [kN]		0,0		0,0	5,4	7,2	0,0	0,0	0,0	0,0	5,4	7,2
RANGE [kN]		46,1		17,4	40,7	26,2	26,5	46,1	46,8	17,4	40,7	26,2
25 PERCENTILE		5,5		3,9	18,4	20,6	5,2	9,0	5,3	3,8	18,4	20,6
50 PERCENTILE		19,2		4,6	19,3	21,5	19,2	19,1	19,5	4,6	19,3	21,5
80 PERCENTILE		21,6		5,5	20,6	22,7	21,3	21,8	22,6	5,6	20,7	22,7
90 PERCENTILE		22,6		6,4	21,9	23,6	21,9	23,6	36,4	6,5	22,3	23,6
95 PERCENTILE		23,8		7,6	24,4	24,8	22,4	26,5	38,6	7,6	25,1	24,8
# OF POINTS		64 308		16 926	22 338	22 338	12 204	21 648	30 456	16 926	19 632	22 338
SAMPLE VARIANCE		61,3 mil6		4,0 mil	10,9 mil	4,5 mil	57,0 mil	61,5 mil	114,3 mil	4,0 mil	12,3 mil	4,5 mil
KURTOSIS		-0,9		6,0	15,7	5,1	-1,4	-0,2	-0,4	5,8	13,5	5,1
SKEWNESS		-0,5		1,1	2,8	-0,2	-0,7	-0,4	0,3	1,0	2,6	-0,2
DLC		0,07		0,07	0,03	0,02	0,08	0,08	0,10	0,07	0,03	0,02

1 Million

Table C.7: Summary of statistics for DADS-based tyre load data - STEERING tyre.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	Unladen	Laden	10 % Overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE WHEEL LOAD [kN]	28,7	31,2	30,4	22,4	33,2	34,9	30,1	30,2	30,1	30,1	30,2	30,2
STANDARD DEVIATION [kN]	6,3	10,1	8,1	5,2	6,5	7,3	6,9	8,6	9,0	6,0	7,1	11,3
COEFFICIENT OF VARIATION [%]	21,9	32,5	26,6	23,2	19,7	20,8	23,1	28,3	29,7	20,0	23,5	37,6
MAXIMUM [kN]	48,5	85,6	69,5	62,7	85,6	85,0	56,1	84,8	85,6	46,8	56,4	85,6
MINIMUM [kN]	10,5	-0,3	0,3	-0,3	0,0	0,0	5,4	-0,3	-0,2	17,0	0,3	-0,3
RANGE [kN]	38,0	85,9	69,2	63,0	85,6	85,0	50,7	85,1	85,8	30,8	56,1	85,9
25 PERCENTILE	21,4	23,5	24,3	210,1	30,5	32,2	23,5	23,4	23,2	23,8	24,0	22,0
50 PERCENTILE	31,3	32,3	31,1	22,1	32,8	34,6	31,9	31,4	31,3	32,1	31,5	30,2
80 PERCENTILE	34,0	38,2	36,3	24,9	36,6	38,6	35,3	36,1	36,4	35,2	36,0	38,2
90 PERCENTILE	35,2	42,3	39,4	27,5	39,6	42,0	37,4	39,2	39,6	36,8	38,7	44,6
95 PERCENTILE	36,2	47,2	43,0	31,4	44,0	46,6	40,2	43,5	43,6	38,2	41,1	50,4
# OF POINTS	31 328	36 574	36 590	34 952	34 690	34 892	19 904	36 604	48 050	34 934	34 726	34 900
SAMPLE VARIANCE	39,3 mil7	102,5 mil	65,6 mil	27,0 mil	42,7 mil	52,9 mil	48,3 mil	73,3 mil	80,1 mil	36,1 mil	50,5 mil	128,3 mil
KURTOSIS	-1,2	1,3	1,2	5,3	5,7	5,5	-0,2	1,8	1,7	-1,2	-0,4	0,8
SKEWNESS	-0,4	0,3	0,3	0,5	0,5	0,5	0,0	0,3	0,4	-0,4	-0,1	0,5
DLC	0,07	0,04	0,04	0,04	0,03	0,03	0,04	0,05	0,05	0,03	0,04	0,06

1 Million

Table C.8: Summary of statistics for DADS-based tyre load data – DRIVING tyre.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	Unladen	Laden	10 % Overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE LOAD [kN]	19,0	17,8	17,1	7,5	21,5	23,9	17,7	17,7	17,7	17,6	17,8	17,7
STANDARD DEVIATION [kN]	9,0	8,4	7,2	2,3	3,6	4,2	7,5	8,1	8,3	7,4	7,8	8,9
COEFFICIENT OF VARIATION [%]	47,3	47,0	42,3	30,5	16,7	17,6	42,4	45,7	46,6	42,0	43,9	50,3
MAXIMUM [kN]	51,5	49,9	46,9	32,0	49,8	51,5	39,0	46,3	51,5	32,9	38,4	51,5
MINIMUM [kN]	-1,1	-0,7	-0,7	-1,1	1,3	0,1	1,9	-0,7	-1,1	3,0	-0,5	-1,1
RANGE [kN]	52,6	50,7	47,6	33,1	48,5	51,4	37,0	47,0	52,6	29,9	38,9	52,6
25 PERCENTILE	7,8	8,0	8,9	6,6	19,6	21,8	8,2	8,5	8,5	8,1	8,6	9,0
50 PERCENTILE	23,1	21,1	20,0	7,5	21,4	23,9	21,2	20,5	20,4	21,1	21,0	19,1
80 PERCENTILE	26,5	24,6	23,0	8,7	23,9	26,7	23,9	24,4	24,7	23,8	24,6	25,4
90 PERCENTILE	27,9	26,5	24,6	9,8	25,3	28,5	25,3	26,5	26,9	25,1	26,3	28,5
95 PERCENTILE	29,5	28,7	26,3	11,0	27,0	30,6	26,5	28,4l	28,9	26,2	27,7	31,4
# OF POINTS	62 656	146 296	146 360	118 712	69 357	118 560	66 348	126 480	162 704	118 692	118 292	118 560
SAMPLE VARIANCE	80,9 mil8	70,0 mil	52,1 mil	52,9 mil	12,9 mil	17,7 mil	56,5 mil	65,3 mil	68,2 mil	54,7 mil	61,2 mil	79,0 mil
KURTOSIS	-1,3	-1,1	-0,9	6,8	3,1	2,9	-1,4	-1,1	-1,0	-1,5	-1,3	-0,9
SKEWNESS	-0,4	-0,3	-0,3	0,7	0,0	0,1	-0,5	-0,2	-0,2	-0,5	-0,4	0,0
DLC	0,16	0,06	0,06	0,05	0,03	0,03	0,07	0,08	0,08	0,07	0,07	0,08

1 Million

Table C.9: Summary of statistics for DADS-based tyre load data – TRAILING tyre.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	Unladen	Laden	10 % overloaded	40 km/h	60/80 km/h	90/100 km/h	1,2 HRI	3,1 HRI	5,3 HRI
AVERAGE LOAD [kN]	Not Applicable	15,0	16,7	5,1	20,3	22,6	16,0	16,0	16,0	16,1	15,6	16,0
STANDARD DEVIATION [kN]		8,3	8,7	1,6	3,7	4,5	8,3	8,5	8,7	8,0	8,8	8,9
COEFFICIENT OF VARIATION [%]		55,4	51,8	32,6	18,4	20,0	51,8	53,2	54,4	49,7	55,4	55,3
MAXIMUM [kN]		40,6	48,9	21,1	38,3	48,9	43,2	42,5	48,9	29,0	37,3	48,9
MINIMUM [kN]		-0,6	-0,8	-0,8	2,6	0,0	-0,1	-0,8	-0,4	1,7	-0,3	-0,8
RANGE [kN]		41,3	49,7	21,9	35,6	49,0	34,3	43,3	49,3	27,3	37,6	49,7
25 PERCENTILE		5,3	6,0	4,3	18,4	20,4	5,7	5,7	5,9	5,5	5,9	6,4
50 PERCENTILE		17,9	20,4	5,1	20,5	22,9	19,6	19,2	18,8	20,2	17,8	18,4
80 PERCENTILE		22,0	24,1	6,0	22,9	25,8	23,2	23,4	23,6	22,7	24,5	23,8
90 PERCENTILE		24,6	25,8	6,7	24,9	28,0	25,0	25,3	25,8	23,9	26,7	26,4
95 PERCENTILE		27,1	27,6	7,6	26,4	29,8	26,6	27,2	28,0	24,6	28,3	28,7
# OF POINTS		219 444	292 720	170 832	170 732	170 704	92 920	186 444	233 108	170 876	170 928	170 688
SAMPLE VARIANCE		69 mil9	75,2 mil	27,1 mil	14,0 mil	20,4 mil	69,0 mil	72,3 mil	75,7 mil	63,9 mil	77,3 mil	78,7 mil
KURTOSIS		-1,3	-1,3	4,8	1,0	1,2	-1,4	-1,4	1,2	-1,5	-1,4	-1,1
SKEWNESS		-0,1	-0,4	0,5	-0,3	-0,2	-0,4	-0,3	-0,2	-0,6	-0,1	-0,2
DLC		0,08	0,08	0,05	0,03	0,03	0,09	0,09	0,09	0,08	0,09	0,09

1 Million

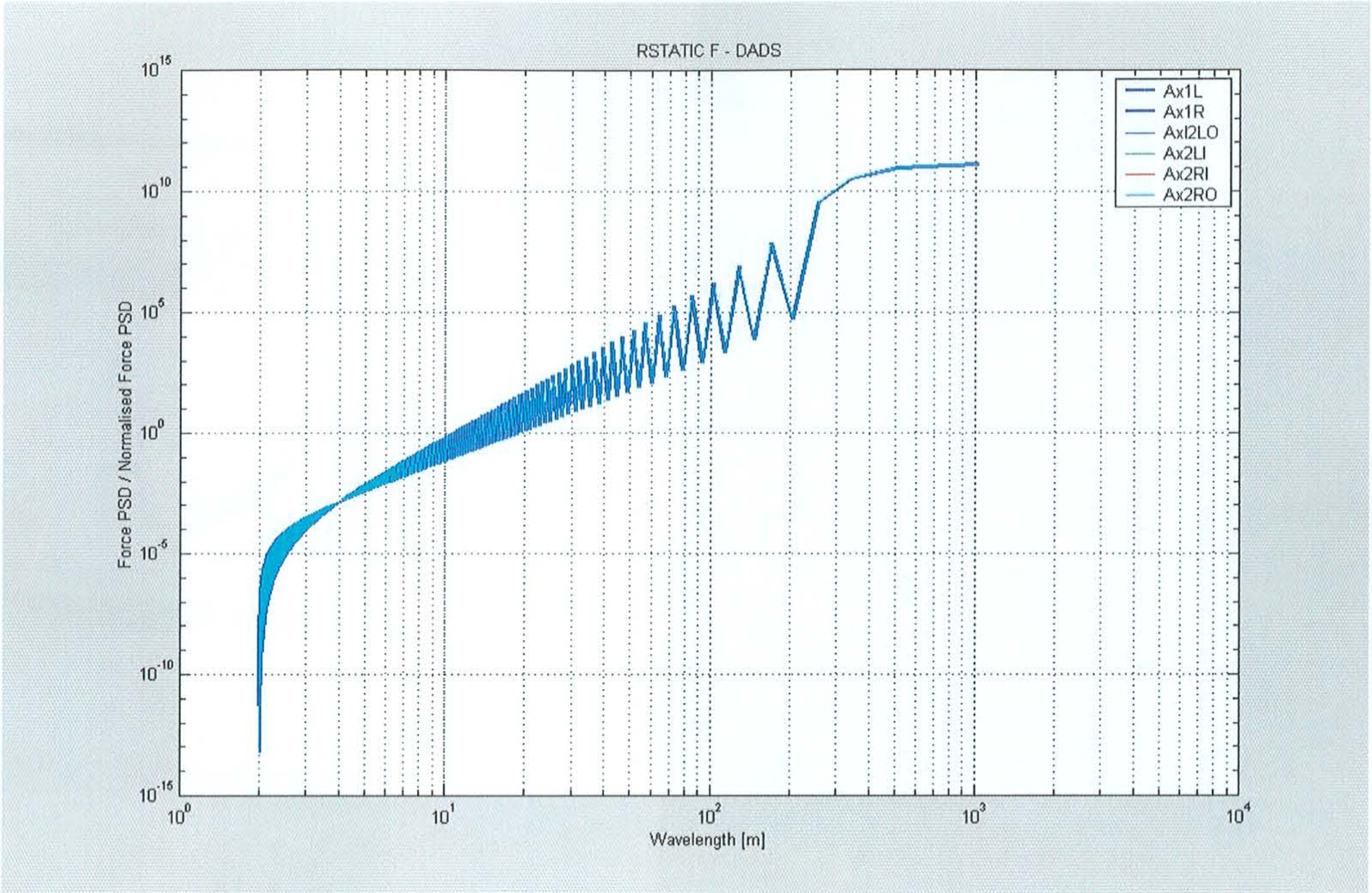
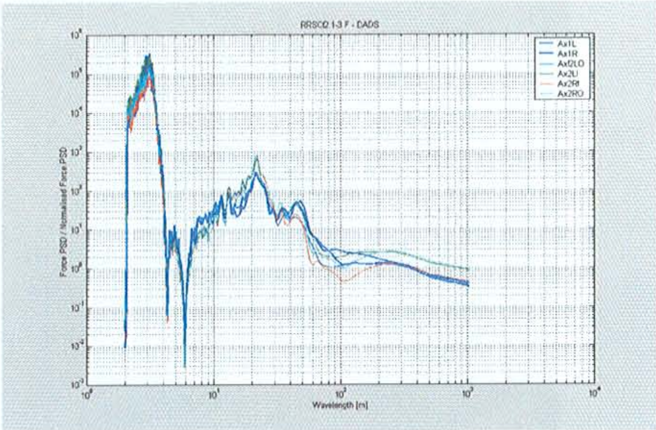
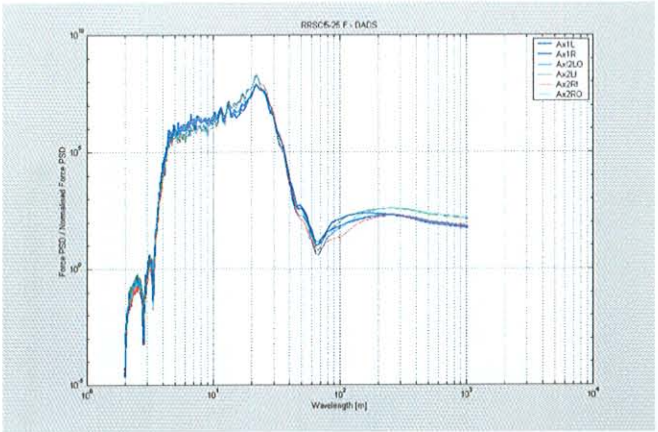


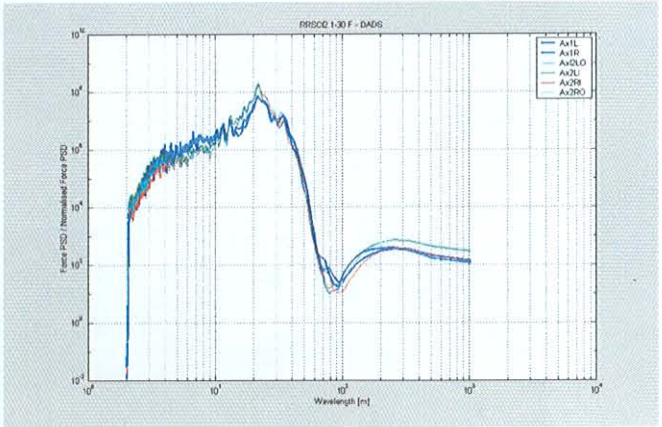
Figure C.1: **PSD of static tyre load indicating frequency band at ultra low (> 100 m) wavelengths.**



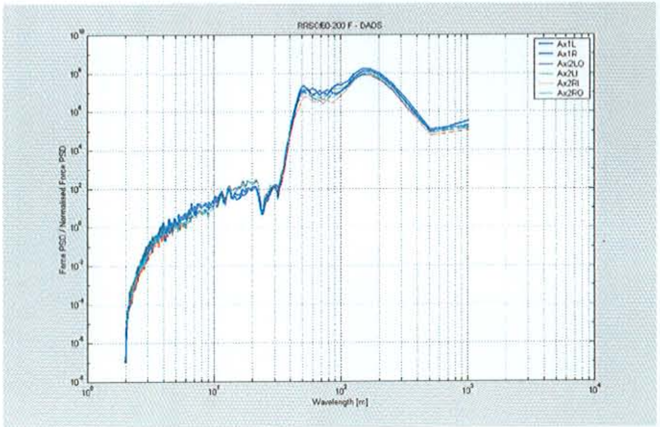
Axle hop frequency



Body bounce frequency



Dynamic component frequency



Ultra low frequency

Figure C.2: Four different frequency bands of PSD curve used in spectral analyses.

APPENDIX D. PROCEDURES, DATA AND RESULTS FOR PAVEMENT RESPONSE ANALYSES

D.1. Introduction

The procedures used to analyse the pavement response discussed in Chapter 6 of this thesis are described in this appendix. This include the specific procedures used, the rationale for using these procedures and the way the procedures interact with each other.

D.2. Pavement Response Analysis Procedures Used

Three procedures were used in the pavement response analyses. The reason for these three procedures was to indicate the effect of pavement response analysis methods at the basic, intermediate and advanced level on the calculated pavement behaviour.

The three procedures selected consisted of a static response method with static tyre loads, a static response method with dynamic tyre loads, and a transient finite element method with transient dynamic tyre loads and transient pavement response.

The material models used for all the analyses are linear elastic models, to enable use of the available South African Mechanistic Design Method (SAMDM) transfer functions.

D.3. Static Response Analysis

The static response analyses were performed using tyre load data from the static condition of all three the vehicles. As there are no transient movements included in the data, the vehicle speed and pavement roughness did not play any role in these analyses.

The Elsym5M (1995) software was used for the analyses in this procedure. The tyre loads were selected as four percentile values of the tyre load population developed in Chapter 5.6. The tyre loads were applied at selected tyre positions for each of the three vehicles, to enable investigation of the effect of the various tyre loads on each other and on the pavement.

The pavement response was calculated at positions indicated in Figure D.1 for each of the load cases. The material input data and pavement structure are shown in Chapter 4 and Table 4.5.

Various combinations of tyre load configurations were used to evaluate the effect of different tyres' loads on the response of the pavement structure. Elsym5m only allows one load magnitude to be applied at load positions for a specific analysis.

The data obtained from the ELSYM analyses were analysed to determine the most critical load positions in terms of the most severe stresses and strains. Analysis of the data indicated that the highest normal, principal and deviatoric stresses, and deflections were obtained directly under single tyres where present, and directly underneath the outer of the dual tyres where these were present. The maximum shear stresses and normal, shear and principle strains were mostly found between the locations of two tyres, or next to the tyre (for single tyres).

The summary of the stresses, strains and deflections calculated using the static response analysis technique is shown in Table D1.

The summary of the expected lives calculated for the static response analysis techniques are shown in Table D.2.

D.4. Transient Response Analysis

The transient response analysis was performed as the advanced technology level analysis of pavement response. In this analysis a finite element approach was used to calculate the transient response of the pavement structure to a dynamically varying transient tyre load. These tyre loads were simulated using the DADS (DADS, 1997) software, as described in Chapter 5.

The transient response analysis was performed using an axi-symmetric finite element package. (Jooste, 1999), with only the input tyre load of the left front steer tyre. The procedure used for the axi-symmetric pavement response calculations are as follows. The damping parameter is firstly calibrated by calculating the static response of the pavement structure to the applied load using the ELSYM software. The finite element analysis is performed with the load applied as a haversine load applied for a period of up to 10 seconds. The objective is to calculate the response of the pavement using the finite element approach to a static load. The damping parameter is selected as that value where critical damping starts to occur, as no vibration of the pavement is normally observed after a load has passed by.

The transient response of the pavement to the load is then calculated by applying the selected load as a sinusoidal load to a contact area (circular, uniform contact stress) on the finite element mesh. The selected loads originate from the population of tyre loads developed for each of the various speeds in Chapter 5 of this thesis. The same four percentile values (50, 80, 90 and 95) as for the static analyses are used). The time for the load to theoretically reach different points on the pavement surface at the selected speed is calculated, and the response of the pavement at the selected positions at this calculated time, is used as the pavement response of the pavement when the load is approaching the centre of the mesh. By calculating these responses at the different time intervals, a response of the pavement to a transient load is calculated.

Once the damping parameter for the specific pavement structure is calculated, the responses of the pavement structure to various speeds can be calculated. Where asphalt is present in the pavement structure, the dynamic modulus of the asphalt layer is calculated at the selected speed, and the specific dynamic elastic modulus for the structure used in the pavement response analysis.

D.5. Static Response Analysis with Speed and Roughness Effects Analysis

The static response with speed and roughness effects analyses were performed using the tyre load data from the tyre load population developed using the output from the various vehicle simulations in Chapter 5. The tyre load data used include the effects of vehicle speed and pavement roughness.

The PADS (Theyse and Muthen, 2000) software was used for the analyses in this procedure. The tyre loads were selected as four percentile values of the tyre load population developed in Chapter 5.6. The tyre loads were applied at selected tyre positions for each of the three vehicles, to enable investigation of the effect of the various tyre loads on each other and on the pavement.

Two analyses were performed using this data set. The first was performed using the data as is, thus increased tyre loads caused by the pavement roughness and vehicle speed, but without any consideration of the decreased pavement response normally observed under increased load application speeds (reference). The second analysis was performed using the same data set, but adapted through the use of a load impulse value that is dependent on the vehicle speed and contact time with the pavement (see Chapter 5.6). The objective of this analysis was to enable a relatively quick calculation of the effect of vehicle speed and pavement roughness on pavement response. The effects of mass and inertia in the pavement are thus incorporated indirectly through a time-dependent factor.

Various combinations of tyre load configurations were used to evaluate the effect of different tyres' loads on the response of the pavement structure. PADS only allows one load magnitude to be applied at load positions for a specific analysis.

D.6. References

ELSYM5M. 1995. **Elsym5M: Analysis of elastic layered systems under normal wheel loads.** Pretoria: Computer Information Centre for Transportation (CICTRAN). Volume 1: PC Version 2.0 – metric. (User Manual DPVT-M27).

JOOSTE, F.J. 1999. **Personal communication on axi-symmetric finite element programme based on Owen and Hinton (1980).** Pretoria: CSIR, Consultant.

THEYSE, H.L. and MUTHEN, M. 2000. **Pavement design and analysis software (PADS) based on the South African mechanistic-empirical design methods.** Pretoria: South African Transport Conference.