5. TYRE LOADING

5.1. Introduction

The second major topic of this thesis is pavement response models, and in particular transient response of pavement structures to loads applied by vehicles. In order to evaluate the response of pavements to load conditions correctly, detailed load functions and a well-founded understanding of tyre loads are needed. In Section 2.4 tyre loading was investigated, to obtain the best current understanding from the available literature.

It falls within the scope of this chapter to focus on the characterisation of tyre loads on the simple and complicated level, to compare the tyre loads developed using different approaches with each other and to provide input data to the pavement response analyses in Chapter 6.

The objective of this chapter is to infer principles of dynamic tyre loading for use in pavement design and analysis.

Detailed tyre load history data are required as input to pavement response analyses. Three levels of technology were selected for generating these tyre load history data in this thesis. These are the simple static, intermediate dynamic and complex dynamic levels (see Section 2.4). The input data for these analyses were presented in Section 4.6 and Appendix A. This input data originated from a fingerprinting of South African heavy vehicles.

In this chapter the dominant unit of load used is the load on a single tyre of the vehicle. This approach was selected as the smallest input to any of the pavement response programmes is also the load on a specific tyre, and because it is possible to calculate the loads on any combination of tyres and/or axles when the load on a single tyre is available. Further, the software used to simulate the tyre loads provides the loads applied in this format. Where necessary for comparisons, the tyre loads are converted to axle loads or axle group loads. The wheel for which the loads are given in this thesis is fitted with a 12R22.5 tyre that is used as one half of a set of dual tyres on a normal axle on a truck.

5.2. Data Origin

The available data for analysis consisted of 3 sets of vehicular data describing the behaviour of 3 different vehicles operated over 3 different pavements at 3 different speeds with 3 load levels. The 3 vehicles used are shown schematically in Figure 5.1. The 3 sets of data were developed using a static approach, an intermediate approach (Tire Force Prediction programme (TFP) analysis) and a complicated approach (Dynamic Analysis and Design System (DADS) analysis) The procedures for running these analyses and the parameters used in each of the analyses are described in Sections 2.6 and 4.6 and Appendix A.

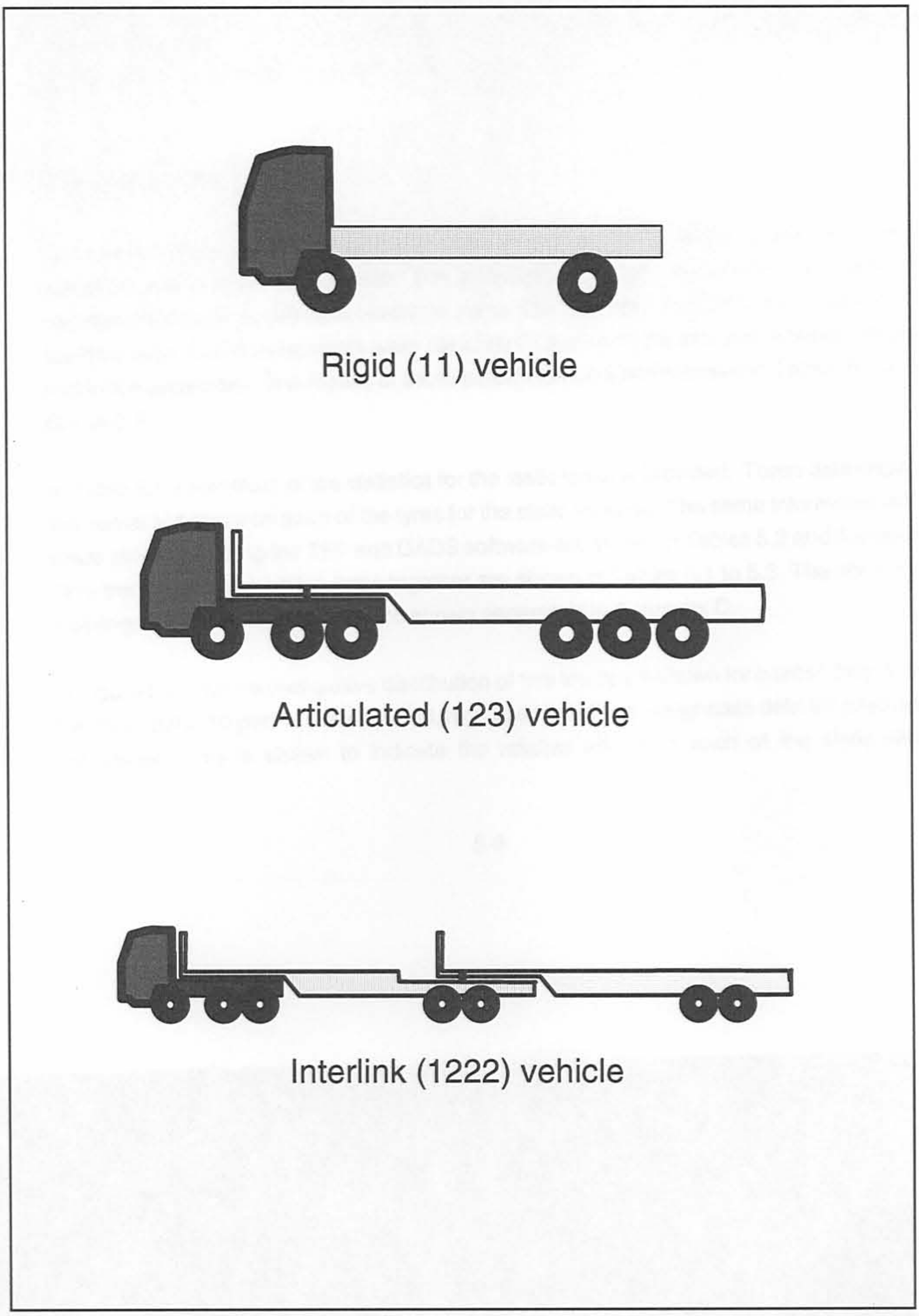


Figure 5.1: Schematic of 3 vehicles used in tyre load simulations.

The large data set on which the statistical analyses had to be performed (up to 468 000 tyre loads per data set) necessitated samples from the full data sets to be used. This was mainly due to size limitations in the software used for the statistical analyses. Initially the tyre load data as developed using the vehicular simulation software, were analysed to obtain the statistics and frequency contents of the complete data sets. This background was used to select decision criteria on which samples from the data were obtained. A sample from the constant speed tyre data was selected that represented a 10 second continuous set of data, towards the end of the constant speed portion of the simulation. This was to prevent possible effects from the acceleration phase to be included in the data. (The focus in this thesis is only on constant speed data).

The intermediate program selected for use in this thesis is TFP (see Section 2.4.3). Two vehicles were simulated as running over 3 pavement profiles at 3 speeds and with 3 load levels. This is similar to the analysis performed for the complex model, except for the interlink (1222 vehicle) which cannot currently be analysed using the TFP software. A total of 54 load histories were developed in this way. As TFP does not analyse roll in a vehicle, tyre loads for the left and right side of the vehicle are similar. The simulations were performed at a constant speed over the selected pavement sections.

The complex program selected for use in this thesis is DADS (see Section 2.4.3). Three typical vehicles were simulated as running over 3 pavements having different pavement roughnesses. Three typical speeds were used for each vehicle. A total of 81 tyre load histories were obtained. As DADS does include the effect of roll in the analysis, different data were obtained for the left and right sides of the vehicles. The simulations were performed as realistically as possible, with all vehicles starting from standstill and accelerating at a realistic rate until the selected constant speed was reached. The simulation then ran for at least 1 000 m at this speed, where after the vehicle braked for at least 5 seconds (Gilliomee, 1999).

5.3. Data Characterisation

The tyre load data obtained from the simulations and sampling were characterised using both a statistical and a spectral approach. The statistical approach consisted of calculating various standard statistical parameters (average, percentile, standard deviation, skewness, kurtosis) of the data sets. These parameters were calculated for each of the vehicles, speeds, roughnesses and loads separately. The results of these calculations are summarised in Tables 5.1 to 5.3, and C.1 to C.9.

In Table 5.1 a summary of the statistics for the static loads is provided. These data originate from the actual tyre loads on each of the tyres for the static vehicles. The same information for the tyre loads simulated using the TFP and DADS software are shown in Tables 5.2 and 5.3 respectively. Only the statistics for all the tyres together are shown in Tables 5.1 to 5.3. The statistics for the steering, drive and trailing tyres are shown separately in Appendix C.

In Figure 5.2 a typical cumulative distribution of tyre loads are shown for a set of data. In the figure the static data, 10 per cent overloaded, high speed and high roughness data for a typical vehicle are shown. This is shown to indicate the relative effects of each of the three parameters investigated (speed, pavement roughness and load) on the simulated tyre loads. In Figure 5.3 a typical histogram of simulated tyre loads for the same data set is shown. Discussion of these graphs follows in section 5.4.

The spectral approach consisted of calculating the dominant frequencies present in the sets of tyre load data. This was done using the Power Spectral Density (PSD) approach. Further, the energies for various frequency bands (calculated as the area under the PSD curve) were also calculated. For these calculations the data were filtered to focus on the specified frequency bands. The results of these calculations are summarised in Table 5.3 and C.7 to C.9. Only the results of the spectral analysis for the DADS data are shown in the thesis, as these results were calculated taking into account the roll of the vehicle, and the loads on individual tyres.

In Figure 5.4 a typical PSD curve is shown for simulated tyre loads. On the figure the typical axle hop and body bounce frequency ranges are shown. A typical dominant body bounce frequency is also shown at a wavelength of approximately 21 m. The typical ultra low frequency range indicated (wavelengths longer than 100 m) is the region at which static load data is shown in the PSD. Although this data does not realistically have a wavelength, the mathematical procedure used indicated the PSD of these components as having very long wavelengths. Analysis of a static data set with the PSD approach (see Appendix C) has confirmed this phenomenon.

Using the statistical and spectral approach data, the effects of the parameters varied in the study (vehicle type, speed, pavement roughness, vehicle payload) on the calculated tyre loads were investigated.

5.4. Data Comparison

The tyre load data obtained using the various simulations were analysed to determine how the data for the various tyres, axles and vehicles compared. Firstly the data summarised in the various tables (Tables 5.1 to 5.3 and C.1 to C10) were visually compared. Next, statistical comparisons of the following sets of data were performed:

- Single, tandem and tridem axle data;
- Steer, drive and trail axle group 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;
- Rigid (11), Articulated (123) and Interlink (1222) vehicle data

Table 5.1: Summary of statistics for static tyre load data – ALL tyres.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	0 % (Unladen)	100 % (Laden)	110 % (Overloaded)	40 km/h	60/80 km/h	90/100 km/h	Smooth 1,2 HRI	Average 3,1 HRI	Rough 5,3 HRI
AVERAGE LOAD PER TYRE [kN]	22,0	17,5	17,9	7,9	22,2	24,5						
STANDARD DEVIATION [kN]	9,2	8,7	8,4	5,3	4,1	4,0						
COEFFICIENT OF VARIATION [%]	41,8	49,7	46,9	67,1	18,5	16,3						
MAXIMUM [kN]	33,6	36,3	35,1	23,6	34,5	36,3						
MINIMUM [kN]	7,0	4,3	5,2	4,3	18,4	20,5						
RANGE [kN]	26,6	32,0	29,8	19,3	16,1	15,7						
25 PERCENTILE	20,1	7,1	8,1	5,2	20,3	22,3	Not applicable due to static loads			Not applicable due to static loads		
50 PERCENTILE	23,1	20,5	21,3	5,6	21,3	23,8						
80 PERCENTILE	29,5	22,9	23,8	8,1	21,9	24,4						
90 PERCENTILE	32,2	23,8	24,2	16,5	29,0	31,4						
95 PERCENTILE	33,6	31,9	25,8	22,9	33,6	35,1						
# OF POINTS	18	66	78	54	54	54						
SAMPLE VARIANCE	84,4 mil[1]	75,4 mil	69,9 mil	28,0 mil	16,9 mil	16,0 mil						
KURTOSIS	-0,6	-0,6	-0,8	4,2	3,9	3,3						
SKEWNESS	-0,7	-0,2	-0,4	2,3	2,2	2,0						

1 Million

Table 5.2: **Summary of statistics for TFP-based tyre load data – ALL tyres.**

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	0 % (Unladen)	100 % (Laden)	110 % (Overloaded)	40 km/h	60/80 km/h	90/100 km/h	Smooth 1,2 HRI	Average 3,1 HRI	Rough 5,3 HRI
AVERAGE LOAD [kN]	23,7	19,2	Not applicable due to TFP inability to analyse interlink (1222) vehicles	9,9	27,1	29,6	22,4	23,9	23,7	10,2	23,2	24,5
STANDARD DEVIATION [kN]	8,9	10,0		7,5	10,0	10,8	12,9	13,0	14,0	8,5	7,8	7,3
COEFFICIENT OF VARIATION [%]	37,6	52,2		76,2	36,9	36,6	57,4	54,5	59,2	83,2	33,5	29,8
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]	0,0	0,0		0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
RANGE [kN]	46,0	78,4		49,0	69,0	78,4	52,8	78,4	65,9	49,0	69,0	78,4
25 PERCENTILE	20,0	10,5		4,7	19,4	21,6	13,8	17,2	12,6	4,6	19,0	21,1
50 PERCENTILE	24,8	20,6		6,9	21,7	23,7	21,3	21,5	21,6	6,6	21,1	22,9
80 PERCENTILE	32,1	24,4		19,4	39,4	44,3	36,4	38,5	39,3	21,7	30,3	29,7
90 PERCENTILE	33,6	33,3		21,7	42,3	46,6	43,1	44,1	44,0	24,5	34,5	35,4
95 PERCENTILE	34,6	36,9		23,6	43,8	47,9	45,9	46,4	46,9	26,3	36,9	37,8
# OF POINTS	38 592	128 616		46 716	57 540	57 540	32 544	48 736	79 182	40 284	52 128	57 540
SAMPLE VARIANCE	79,3 mil2	100,5 mil		56,9 mil	100,0 mil	117,2 mil	165,3 mil	169,8 mil	196,9 mil	71,5 mil	60,4 mil	53,5 mil
KURTOSIS	-0,3	0,4		0,6	-0,9	-0,9	-0,7	-0,6	-1,0	0,2	1,6	2,8
SKEWNESS	-0,7	0,3		1,2	0,6	0,7	0,4	0,4	0,2	1,2	0,8	0,7
DLC	0,13	0,07		0,13	0,06	0,06	0,10	0,09	0,10	0,14	0,06	0,05

1 Million

Table 5.3: Summary of statistics for DADS-based tyre load data – ALL tyres.

PARAMETER	VEHICLE			LOAD			SPEED			PAVEMENT ROUGHNESS		
	Rigid (11)	Articulated (123)	Interlink (1222)	0 % (Unladen)	100 % (Laden)	110 % (Overloaded)	40 km/h	60/80 km/h	90/100 km/h	Smooth 1,2 HRI	Average 3,1 HRI	Rough 5,3 HRI
AVERAGE LOAD [kN]	22,2	17,5	17,9	7,8	22,2	24,4	18,3	18,1	18,2	18,2	18,1	18,2
STANDARD DEVIATION [kN]	9,4	9,6	9,0	5,8	5,6	6,0	9,0	9,4	9,6	8,7	9,3	10,1
COEFFICIENT OF VARIATION [%]	42,2	55,1	50,1	73,6	25,4	24,8	49,1	51,8	52,7	47,8	51,4	55,6
MAXIMUM [kN]	51,5	85,6	69,5	62,7	85,6	85,0	56,1	84,8	85,6	46,8	56,4	85,6
MINIMUM [kN]	-1,1	-0,7	-0,8	-1,1	-0,4	-0,1	-0,1	-0,8	-1,1	1,7	-0,5	-1,1
RANGE [kN]	52,6	86,3	70,3	63,8	86,0	85,1	56,2	85,6	86,6	45,0	56,8	86,6
25 PERCENTILE	18,3	7,4	8,1	4,8	19,2	21,3	7,9	8,0	8,1	7,7	8,0	8,5
50 PERCENTILE	24,0	19,6	20,6	6,2	21,4	23,7	20,9	20,5	20,3	21,0	20,4	19,5
80 PERCENTILE	30,9	24,4	24,4	8,6	25,0	27,9	24,5	24,8	25,2	23,9	25,7	25,7
90 PERCENTILE	33,3	27,9	27,0	17,3	30,0	32,3	27,3	28,3	29,0	25,9	28,6	29,9
95 PERCENTILE	34,7	33,0	30,9	22,4	33,3	35,5	32,6	32,7	33,2	32,5	32,3	34,0
# OF POINTS	93 984	402 314	475 670	324 444	323 586	324 156	178 740	349 528	443 862	324 502	323 946	323 784
SAMPLE VARIANCE	87,9 mil[1]	92,8 mil	80,4 mil	33,2 mil	31,8 mil	36,6 mil	80,1 mil	87,7 mil	91,5 mil	75,2 mil	86,9 mil	102,0 mil
KURTOSIS	-0,8	0,4	-0,3	5,9	5,2	4,7	-0,6	-0,1	-0,1	-0,8	-0,8	0,6
SKEWNESS	-0,5	0,3	0,0	2,3	1,4	1,1	-0,1	0,1	0,1	-0,3	0,0	0,4
DLC	0,14	0,07	0,08	0,12	0,04	0,04	0,08	0,09	0,09	0,08	0,09	0,09
Dominant body bounce frequency [Hz]	2,8	2,5	2,3	3,2	2,3	2,1	2,4	2,4	2,7	2,6	2,5	2,5
Dominant axle hop frequency [Hz]	14,1	15,7	15,3	15,0	14,7	15,4	12,2	16,7	16,2	15,0	15,2	14,9

1 Million

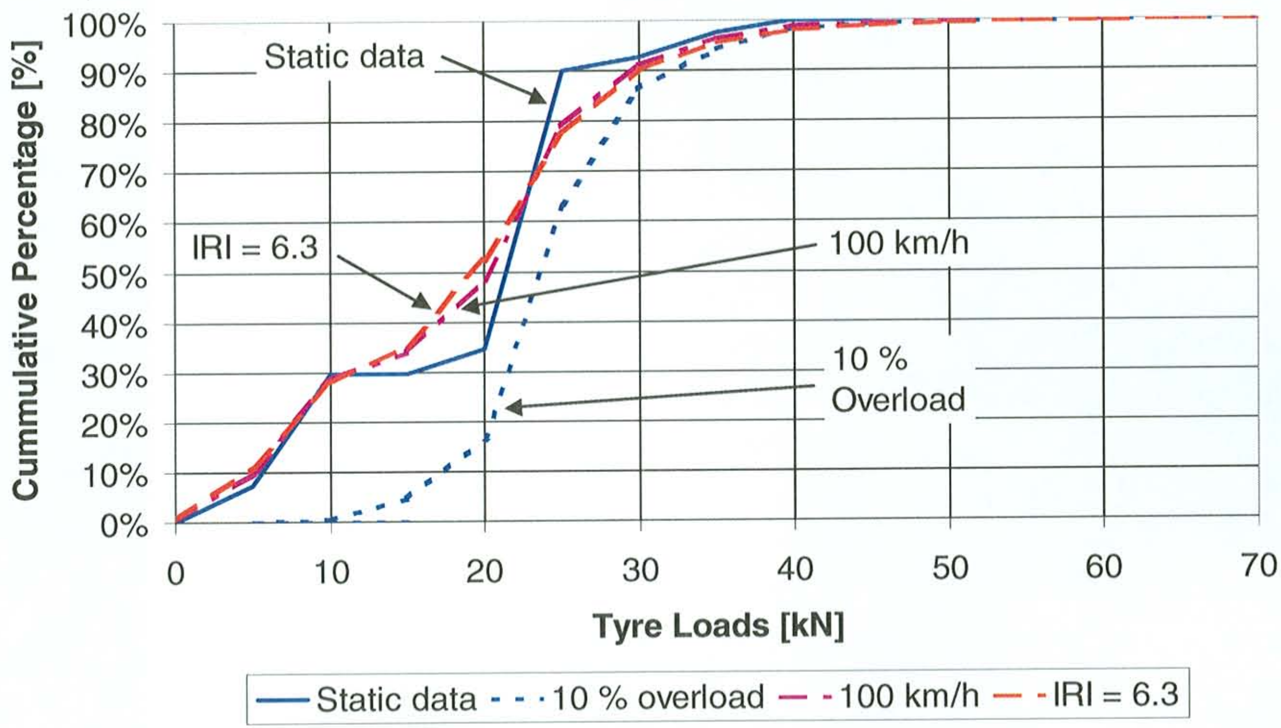


Figure 5.2: **Cumulative distribution of tyre loads of all vehicles as simulated using DADS software.**

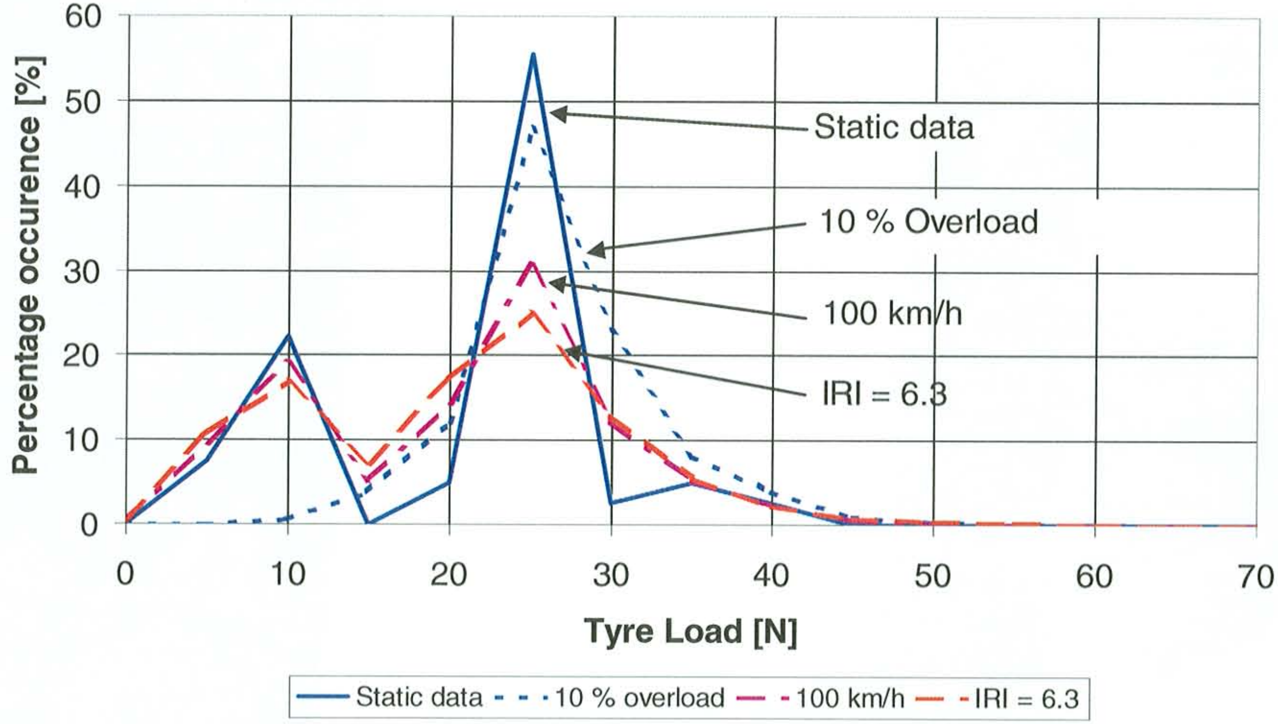


Figure 5.3: **Histogram of tyre loads of all vehicles as simulated using DADS software.**

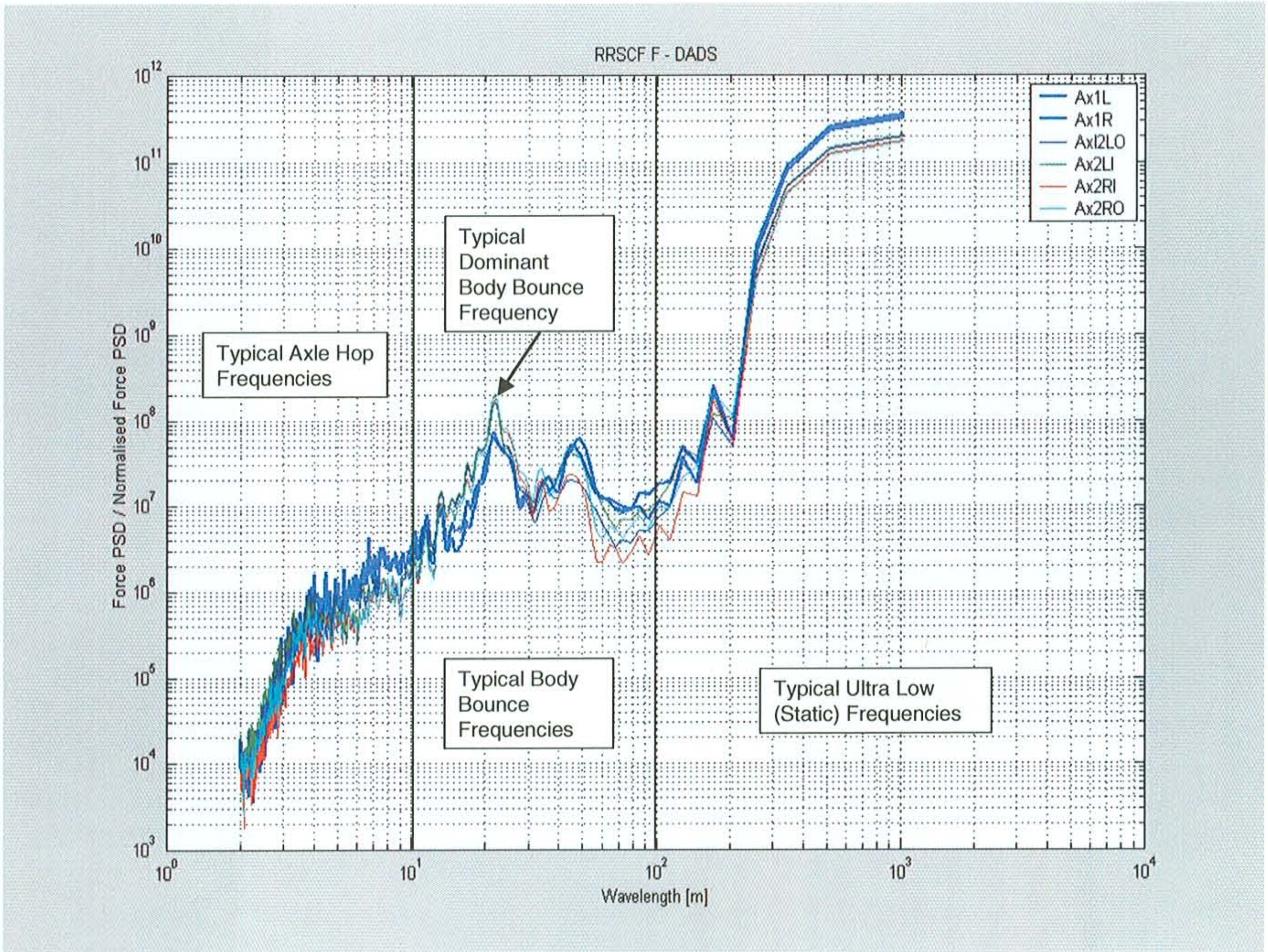


Figure 5.4: Typical Power Spectral Density (PSD) plot for tyre loads, indicating typical axle hop, body bounce and ultra low frequencies.

The visual comparison of the data in the various tables indicated the following clear and general trends (these are trends which are true for all three of the data sets):

- The average tyre loads decreased as the number of tyres on a vehicle increased and increased as the payload on the vehicles increased;
- The standard deviation in tyre loads increased as the vehicle speed increased;
- The coefficient of variation (CoV) of the tyre loads decreased with increased payloads;
- The maximum tyre loads increased with both increased payloads and pavement roughness;
- The minimum tyre loads increased with increased payloads and decreased with increased vehicle speed and pavement roughness;
- The range of tyre loads increased with increased pavement roughness;
- The sample variance increased with increased vehicle speed;
- The Dynamic Load Coefficient (DLC) decreased with increased payload.

An initial conclusion from this comparison is that it appears that the average tyre load and DLC are functions of the actual load on the vehicle, while the standard deviation, CoV and range are functions of the vehicle speed and pavement roughness.

The nominal results of the statistical comparisons between the various sets of data are summarised in Table 5.4. A t-test was run to test for differences between the means, an F-test to test for differences between the standard deviations, and a Mann-Whitney W test to test for differences between the medians of the data sets. A Kolmogorov-Smirnoff test was used to test for differences in distributions.

This comparison of the data from the various tyres provided the following information. None of the groups of data used in the comparisons showed statistically significant differences in the groups themselves. Statistically significant differences with a confidence level of 95 per cent were calculated for most of the data sets. The only data sets where these differences did not exist were for the drive axle data for the TFP and DADS data (means), the single axle and steer axle data (average and standard deviation), and the left and right DADS data (standard deviation).

The tyre loads applied by different axle combinations (single, tandem and tridem) to the pavement differed statistically significantly from each other. The tyre loads applied by the steer, drive and trailing axles on a vehicle also differed statistically significantly from each other. The reason for the differences between the steer/single and the drive/trail and tandem/tridem axles can be seen in Figure 5.4. Most of the differences between these two main groups lie in the fact that all the steer axles are single axles. These axles are less affected by the payload on the vehicle, and thus do not show the initial high percentage of tyre loads at relatively low tyre loads (caused by the unladen vehicles in the analyses). The relationship between the tandem / tridem and drive / trail axle data stems from the fact that the drive and trail axles are mostly tandem and tridem axles for the analyses performed (except for the 11 rigid vehicle). There is, however, still a statistically significant difference at the 95 per cent confidence level between the parameters of these data sets (Table 5.4).

Table 5.4: Results of comparisons between data sets.

	Single DADS	Tandem DADS	Tridem DADS	All DADS	All TFP	Drive DADS	Trail DADS	Steer TFP	Drive TFP	Trail TFP	Right DADS	123 Articulated	1222 Interlink
Single DADS		amsd	amsd										
Tandem DADS			amsd										
All TFP				amsd									
Static				amsd	amsd								
Steer DADS	md					amsd	amsd	amsd	amsd	amsd			
Drive DADS		amsd	amsd				amsd	amsd	asd	amsd			
Trail DADS		amsd	amsd					amsd	amsd	amsd			
Steer TFP									amsd	amsd			
Drive TFP										amsd			
Left DADS											amd		
11 Rigid												amsd	amsd
123 Articulated													amsd

a - average values show statistically significant differences at the 95 per cent confidence level.
m - mean values show statistically significant differences at the 95 per cent confidence level.
s - standard deviation values show statistically significant differences at the 95 per cent confidence level.
d - distribution shows statistically significant differences at the 95 per cent confidence level.

The data from the comparison between the left and right sides of the vehicles indicated that a statistically significant difference with a confidence level of 95 per cent exists between the data sets for the average, mean and distributions, but not for the standard deviations. The data is shown in Figure 5.5 where the relatively small differences can be seen. The possible reason for these differences are the camber in the pavement (5 per cent used in the DADS simulation) which cause the tyre loads on the left side of the vehicle to be higher than that on the right side of the vehicle, causing the difference in mean and median values.

The data obtained from the DADS simulation differed from the data obtained from the TFP simulation, and both the DADS and the TFP data differed from the static data set. It appears from Figures 5.3, 5.7 and 5.8 that the static data are centred around two regions. These are the unladen drive and trail axles (around 10 kN tyre loads) and then the laden and 10 per cent overloaded axles (around 25 kN tyre loads). The simulated dynamic load histories from the TFP and DADS simulations, however, show a higher spread of values (higher standard deviation) around these two data points. Therefore, the effect of the dynamic component of the tyre loads is that the tyre loads are spread along a wider range of tyre loads than when only the static tyre loads are considered.

The histogram in Figure 5.2 is affected severely by the selection of only 3 load cases (unladen, laden (100 per cent payload) and 110 per cent payload). It is believed by the author that a much smoother histogram would result from selecting a continuous range of tyre loads, as would be found in reality. Such a range of load options was not economically feasible for this thesis.

The TFP-simulated data have higher average and median values, and also standard deviations than the DADS-simulated data. Possible reasons for this may lie in the fact that the TFP simulation does not account for any roll motion, the suspension model used to characterise the vehicle in the two simulations and the simplifications used to enable the TFP model to be more simple than the complicated DADS model. It appears from Figure 5.8 that the TFP-simulated data will overestimate the tyre loads.

The data from the comparison between the three types of vehicles indicated that statistically significant differences exist with a confidence level of 95 per cent between the tyre loads from the rigid (11), articulated (123) and interlink (1222) vehicles. In Figure 5.9 the cumulative distribution for these three data sets are shown. It appears that the data for the 123 and 1222 vehicles are closer related than between the 11 vehicle and any of the other two vehicles. This may be because of the 11 being a rigid vehicle with two single axles, and the 123 and 1222 being combinations between truck-tractors and semi-trailers with tandem and tridem axles carrying the bulk of the payload. The GVM of the 123 and 1222 vehicles are also closer related to each other than to the 11 vehicle's GVM. The tyre loads of the unladen vehicles cause the initial sharp increase in the tyre loads. The tyre loads are grouped around a lower point of 6 kN and a higher point of approximately 24 kN, indicating the unladen and laden conditions.

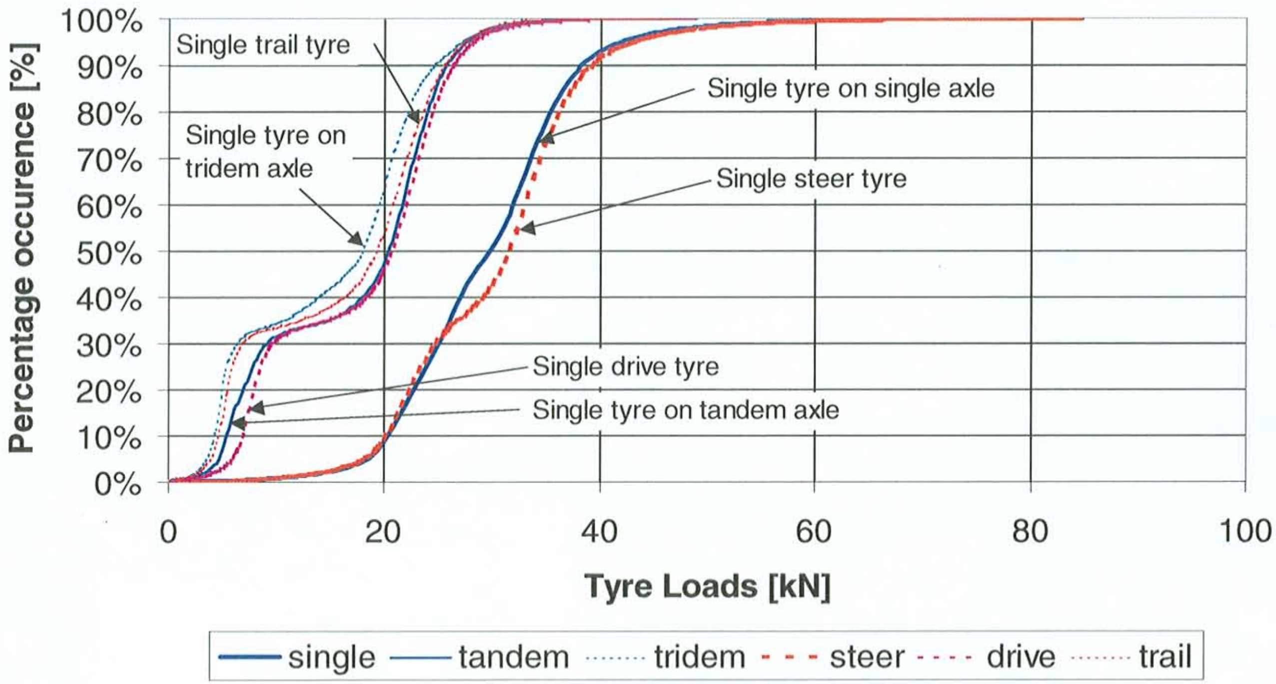


Figure 5.5: **Relationship between single, tandem and tridem and steer, drive and trail axles for all vehicles and conditions simulated (DADS simulated data).**

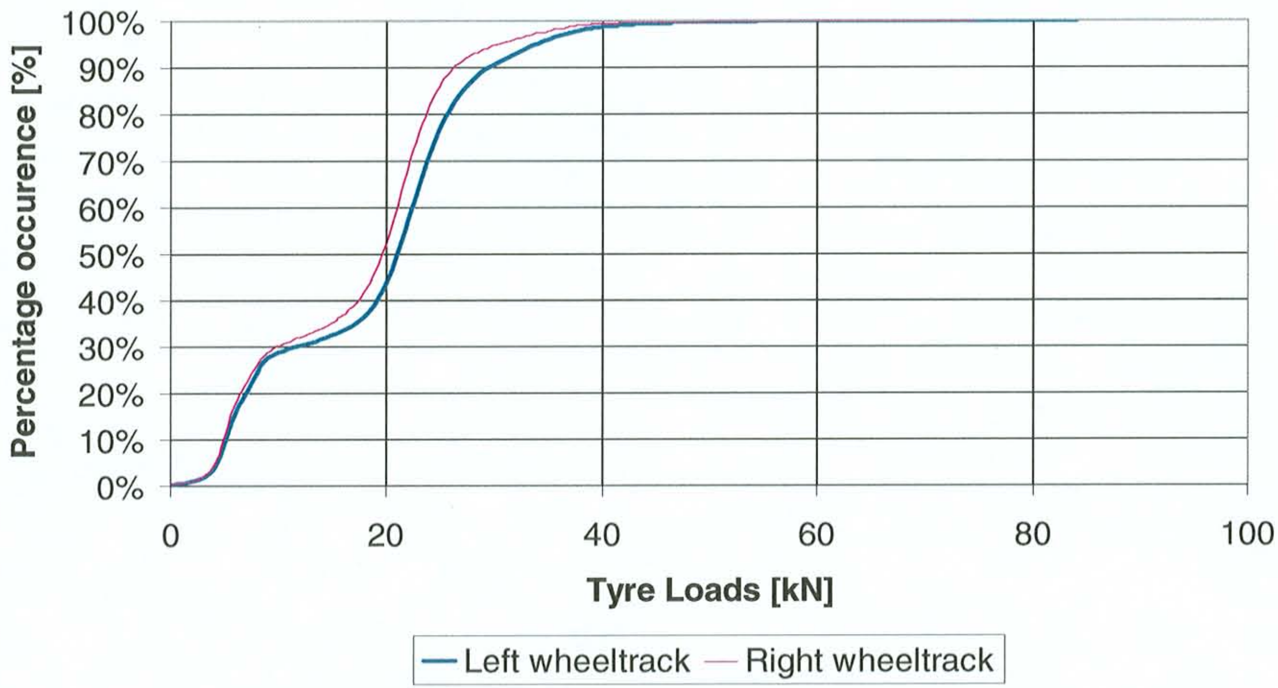


Figure 5.6: **Comparison between left and right wheeltrack tyre load data for all vehicles and conditions simulated (DADS simulated data).**

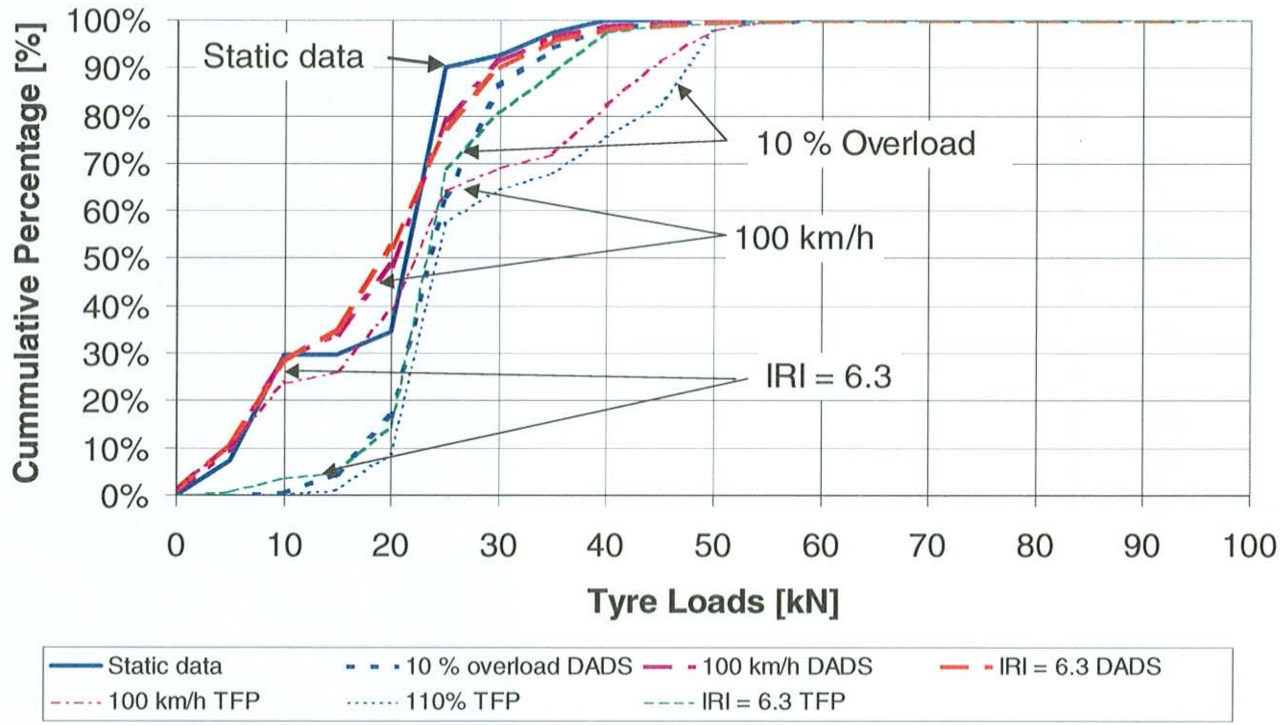


Figure 5.7: **Comparison of data obtained from static and DADS and TFP simulations for all vehicles and indicated conditions.**

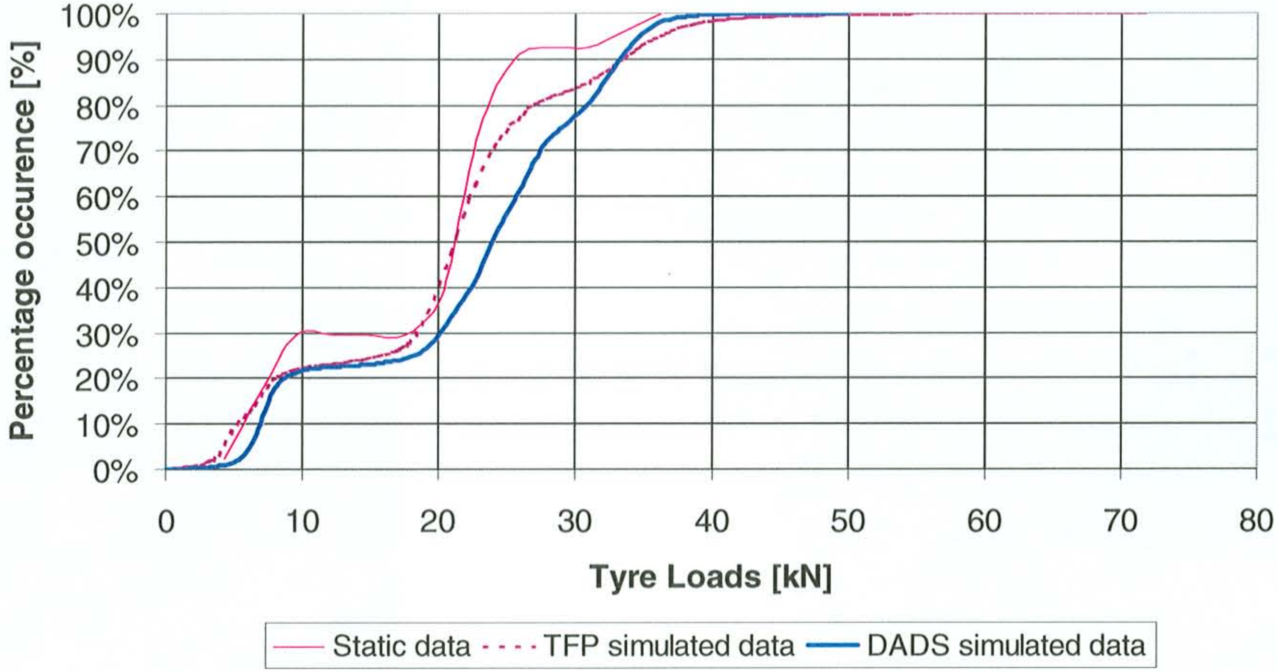


Figure 5.8: **Relationship between static, TFP and DADS data for all vehicles and conditions simulated.**

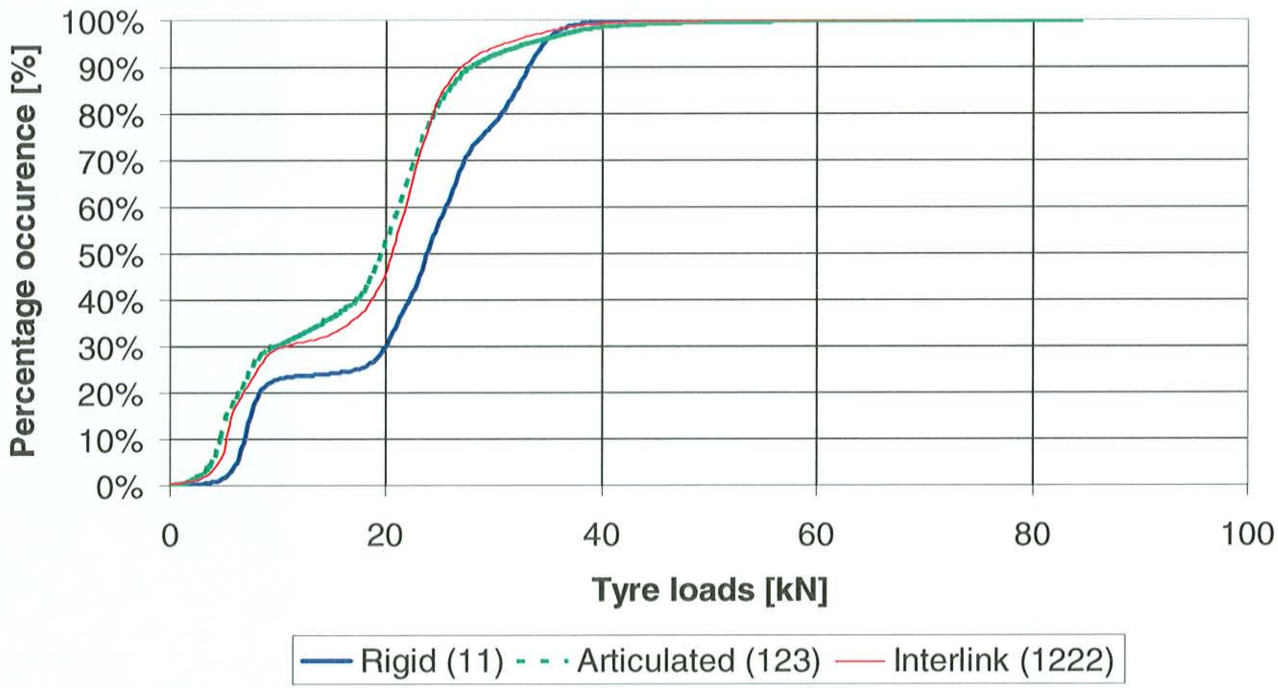


Figure 5.9: **Cumulative distributions of tyre loads for Rigid (11), Articulated (123) and Interlink (1222) vehicles.**

The data from the laden data set containing all the axles and vehicles are used in further analyses in this thesis. The reason for this decision (even though the statistical analyses indicated that the various data sets are statistically different) is that the focus of this thesis is on a phenomenological and practical approach to vehicle-pavement interaction. In practice, the vehicle population deliver their loads to the pavement as single tyre units, and not as axle groups. All of the loads are also applied randomly to the pavement, and not only loads from a specific range of vehicles or axle group. It thus makes practical sense to analyse the effect of tyre loads on the pavement as the overall effect of the vehicle population.

5.5. Tyre Load Discussion

The simulations of tyre load data and analyses thereof described provide several interesting inferences. In this part the relationships between parameters and their effects on the tyre loads are discussed.

In the statistical approach the standard statistical parameters for the tyre load data were calculated. When these statistics are evaluated, it appears that the following holds true for the parameters:

The average vehicle loads are not affected statistically significantly by the pavement roughness or vehicle speed. A high correlation is found between Average vehicle loads and Gross Vehicle Mass (GVM) per tyre, independent of the speed and pavement roughness (Equation 5-1). Conversely, the Coefficient of Variation (CoV) of the vehicle loads show good relationships with the vehicle speed, vehicle type, pavement roughness, vehicle load (in terms of the percentage of laden payload) and GVM (Equation 5-2).

$$\text{Average Load} = 12{,}6 + 1{,}003 * (\text{GVM/Number of tyres on vehicle})$$

$$\text{Average Load [N]}$$

$$\text{GVM [N]}$$

$$R^2 = 99{,}9\ \%$$

$$\text{Correlation Coefficient} = 0{,}999$$

$$\text{Standard error of y} - \text{estimate} = 97{,}1$$

Equation 5-1: Relationships between Gross Vehicle Mass, vehicle type and Average tyre load.

$$\text{CoV Load} = 0{,}39 - 4{,}0E - 7 * \text{GVM} - 0{,}003 * \text{Load} + 0{,}01 * \text{number of tyres} + 0{,}03 * \text{roughness} + 0{,}001 * \text{speed}$$

CoV Load [%]
GVM [N]
Load [%]
roughness [HRI]
speed [km/h]
$R^2 = 94{,}9\%$
Standard error of y – estimate = 0,055

Equation 5-2: Relationship between Coefficient of Variation of tyre loads (CoV Load) and vehicle speed, pavement roughness and vehicle type.

The statistical analyses also indicated that the tyre loads are mostly normally distributed, with slight skewness and/or kurtosis in some cases. This is in agreement with other researchers (i.e. Sweatman, 1983). In general, the distribution can however be described as normal, as the reason for the skewness and kurtosis mostly lie in the fact that the data used in the analysis did not represent a continuous speed, load and roughness range. The vehicle payloads were especially a cause of skewness and kurtosis as only three load levels (unladen, laden and 110 per cent payload) were simulated.

The effects of changes in vehicle speed and pavement roughness (as calculated using Equations 5-1 and 5-2) are shown graphically in Figures 5.10 and 5.11. A change in pavement roughness from 1 to 6 IRI (roughly the range of values used in this thesis) with all other parameters constant, cause an increase in CoV of 0,21 to 0,33. An increase in vehicle speed from 40 km/h to 100 km/h (also the range used in this thesis) cause an increase in CoV from 0,2 to 0,26.

Investigation of the tyre load distributions shows that the main effect of variations in vehicle speed and pavement roughness is directly proportional to variations in the standard deviation of the tyre loads. Increases in any or both of these two parameters thus cause a wider distribution of the tyre loads around the mean. The net result is that a higher proportion of peak loads (and minimum loads) are applied to the pavement. As the damage relationship for tyre loads to a pavement is generally an exponential relationship, these increased peak loads cause even higher damage increases to the pavement. All of this will happen with the same average GVM on the vehicle population. The effect of this is shown schematically in Figure 5.12. An increase in GVM will shift the whole distribution, but will have limited effect on the CoV.

Detailed analysis indicated that under high speed and roughness and low load conditions, the tyre may loose contact with the pavement for up to 0,20 per cent of the distance travelled.

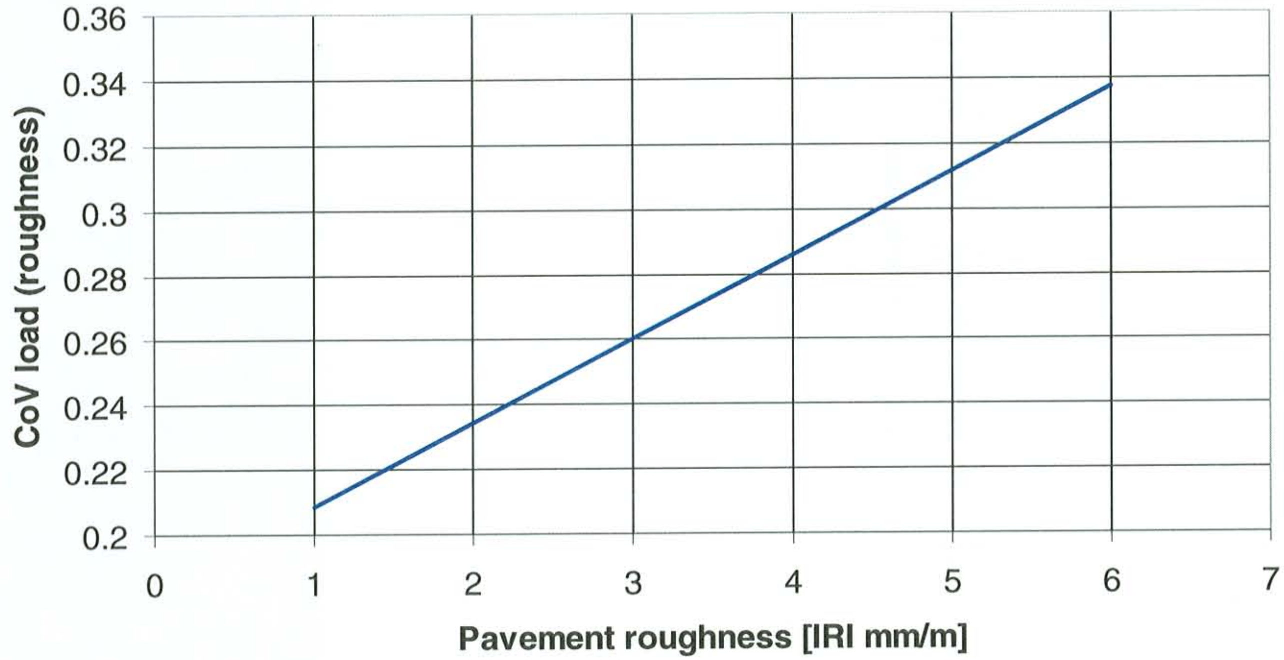


Figure 5.10: **Effect of pavement roughness on Coefficient of Variation (CoV) in tyre load (based on Equations 5-1 and 5-2).**

Figure 5.11: **Effect of vehicle speed on Coefficient of Variation (CoV) in tyre load (based on Equations 5-1 and 5-2).**

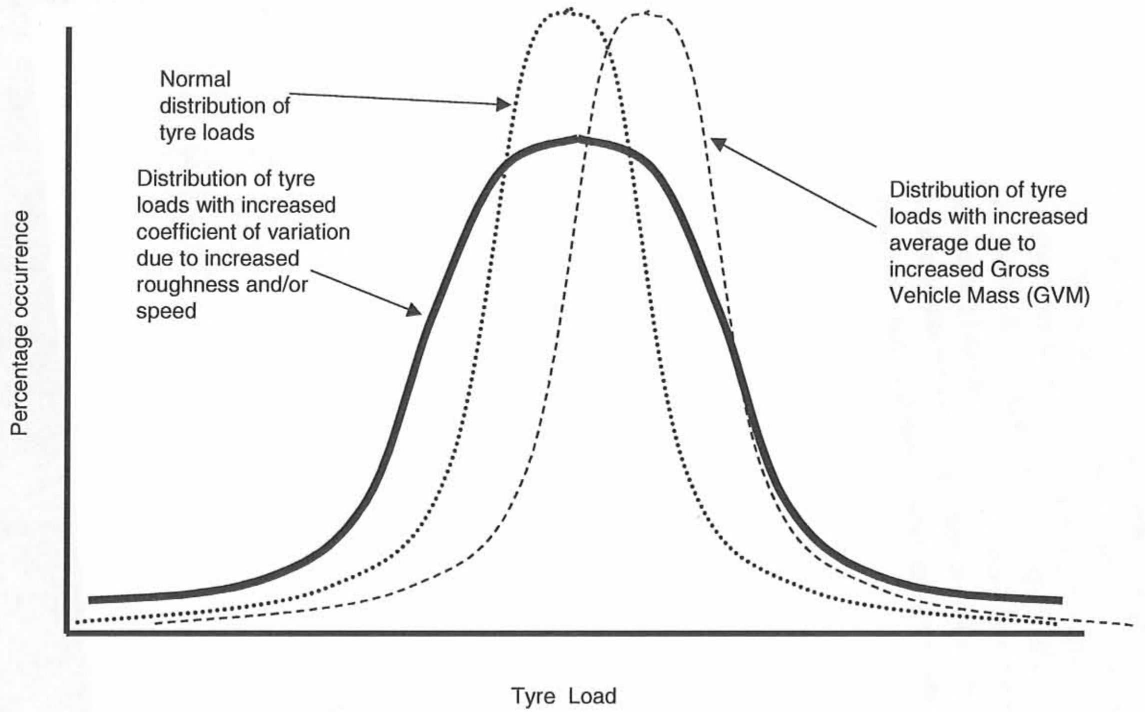


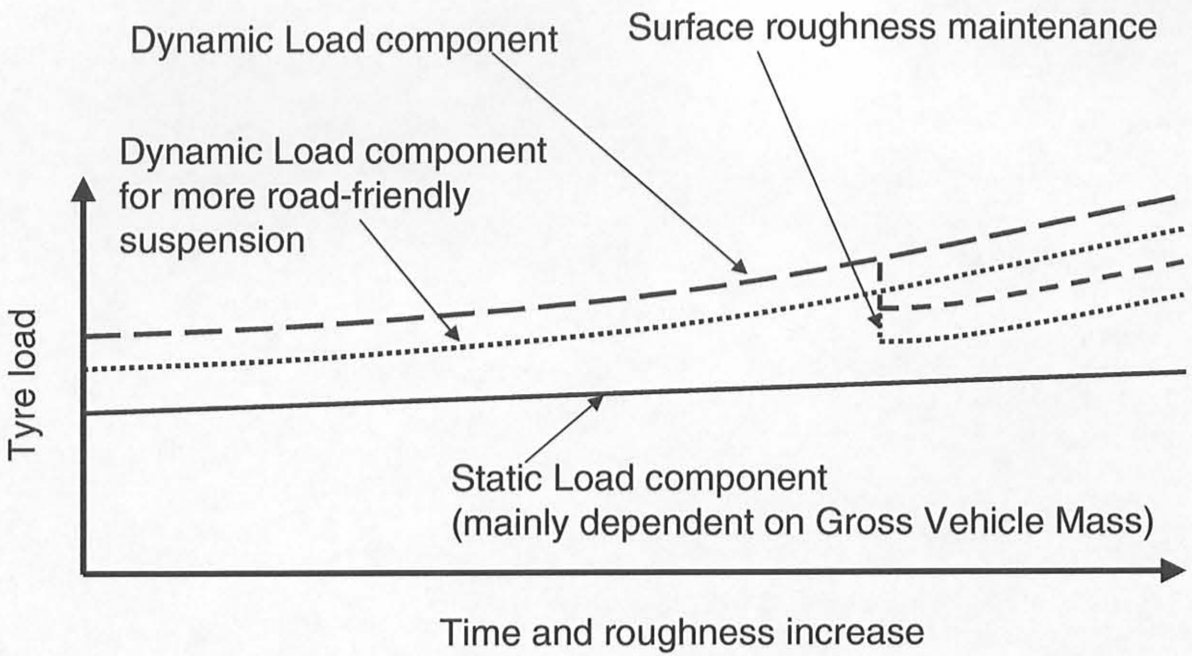
Figure 5.12: Schematic of changes in average and standard deviation of tyre loads.

In practice, these relationships between GVM and average load, and vehicle speed, pavement roughness and coefficient of variation of the tyre load population can be seen as indicating the relationship between the road owner and user. The road user is mainly responsible for the GVM of the vehicle, and also has limited control over the speed. The road user can thus move the average tyre load of the vehicle population. The road owner is mainly responsible for the pavement roughness, and also has limited control over the speed. The road owner can thus change the standard deviation or spread of tyre loads on the pavement by maintaining the pavement roughness at acceptable levels. The dynamic component of the tyre loads is thus mainly the responsibility of the road owner. The road user may contribute to this responsibility by fitting more road-friendly suspensions (an aspect not covered in this thesis) but this will only have a once-off effect, and increases in pavement roughness will then again lead to increased dynamic loads. This phenomenon is shown schematically in Figure 5.13.

As a strong relationship (R^2 = 99,9 %) exists between the average tyre load and the GVM of the vehicles, and a strong relationship (R^2 = 94,9%) exists between the Coefficient of Variation of the tyre loads and the vehicle speed, type, GVM, load and pavement roughness, and the distribution of tyre loads is normal, these parameters (average and Coefficient of Variation) can be calculated for a given population of vehicles, speeds and pavement roughnesses, and the expected distribution of dynamic tyre loads for this population calculated. The relationships in Equation 5-1 (average) and 5-2 (Coefficient of Variation) can be used for this calculation. The tyre load distribution developed can then be used to select design loads at specified percentiles depending on the importance of the pavement.

Using the results of the statistical approach of the tyre loads, the following can thus be stated:

The tyre load consists of two components. The one component is the static load component while the other component is the dynamic component. The static component is directly related to the GVM of the vehicles that use the pavement, and can be mainly be affected by the road user. The dynamic component is directly related to and dependent on the vehicle speed, type, GVM, load and pavement roughness. It is mainly the responsibility of the road owner to control this component (although the GVM and load are the responsibility of the road user). This example illustrates that pavement damage and deterioration are not caused by either the road owner or the road user, but such deterioration is a joint effect.



Static Load component = f(Gross Vehicle Mass)

Dynamic Load component = f(Pavement roughness, Speed)

Figure 5.13: **Schematic indication of the static and dynamic components of tyre load, and the effect of fitting more road-friendly suspensions and improvement of surface roughness.**

Analysis of the spectral content of the tyre loads indicated that the ultra low frequencies (wavelengths of > 100 m and indicative of the static component of the tyre load) are affected by the product of the Gross Vehicle Mass, the pavement roughness and the speed (Equation 5-3). The dynamic component of the tyre loads (wavelengths < 100 m) are affected by the product of the pavement roughness, vehicle speed and vehicle type (Equation 5-4). Vehicle type was defined as the number of tyres on a vehicle. These relationships were developed using the energy of the PSD curve (the area underneath the curve) to relate to the various parameters (GVM, vehicle speed, pavement roughness and vehicle type).

$$\text{Lowfrequency} = -2{,}1\text{E}7 + 1{,}5 * \text{GVM} * \text{roughness} * \text{speed}$$

Lowfrequency [Nm]
GVM [N]
roughness [HRI]
speed [km/h]
$R^2 = 76.6\ \%$
Correlation Coefficient = 0,88
Standard error of y – estimate = 6,1E7

Equation 5-3: Relationship between Low frequency spectral content and Gross Vehicle Mass, pavement roughness and vehicle speed.

$$\text{Dynamic component} = (1\,072 + 1{,}3 * \text{roughness} * \text{speed} * \text{number of tyres})^2$$

Dynamic component [Nm]
roughness [m/m]
speed [km/h]
$R^2 = 81{,}9\ \%$
Correlation Coefficient = 0,91
Standard error of y – estimate = 2 082,78

Equation 5-4: Relationship between Dynamic component spectral content and pavement roughness, vehicle speed and vehicle type.

The effect of these relationships is that although the average load on the pavement (GVM related) may stay constant, both the static and dynamic components of the tyre load will increase due to increases in pavement roughness and/or speed. Pavement deterioration that causes pavement roughness increases cost the road owner more through increased tyre loads. As these increases normally manifest in terms of a higher percentage of peak loads (for a constant GVM), the effect on the pavement is even quicker deterioration as the effect of these overloads (through the exponential damage relationship) are exponential. In Figure 5.13 these increases in tyre load is shown, together with the anticipated effect of road maintenance on the tyre loads.

A hypothesis that will be investigated further after the pavement response analyses are performed is that the static component of the tyre loads (ultra low frequencies, GVM dependent) affects the deterioration of the whole pavement structure, while the dynamic component (high frequencies, speed and roughness related) affects mainly the surface layers of the pavement structure.

In summary, it can be stated that the main objective of optimising tyre loads is to keep the dynamic portion of the tyre load (affected mainly by the pavement roughness and vehicle speed) as small as possible. This should decrease the portion of peak loads on the pavement, thereby causing the loads to be distributed closer to the average tyre load (lower Coefficient of variation in tyre loads).

5.6. Pavement Input Data

The data to be used for the pavement response analyses in Chapter 6 are extracted from the tyre load data described in this chapter. Three types of tyre load data are needed. These are for the static analysis, the intermediate analyses and the advanced analyses.

The data for the static (simple) pavement response analyses are taken from the tyre load distribution data. As the smallest unit used as input in the pavement response calculation is a single tyre, the tyre load for such a tyre is selected at a specific percentile from the distribution of tyre loads calculated. For a standard axle (single axle with dual tyres) to be analysed, the tyre load is applied as four individual loads on the surface of the pavement without any speed component.

The population of tyre loads from which the specific static loads are selected, is that made up by a combination of all the vehicles, loads, speeds and pavement roughnesses used in this thesis. The objective of using this population is to obtain a realistic tyre load as would be expected on a normal highway (thus mixture of traffic and operating conditions).

Four different tyre load percentiles will be used in the pavement analyses. These are in accordance with TRH4 (1996) that indicates the percentile values to be used for design of a class A, B, C and D road to be the 95th, 90th, 80th and 50th percentile. The selected tyre loads for use in the static pavement response analyses are shown in Table 5.5. The percentile tyre load is shown together with the axle load (standard single axle with dual tyres), and the equivalent 80 kN value for the selected loads. An exponent of 4,0 is used in converting the tyre loads to E80s to ensure that a general estimate of the equivalent loads can be provided. For a more comprehensive understanding the value of this exponent can be varied. Higher values (i.e. 6) should cause a higher percentage of peak loads while lower exponents (i.e. 2) should cause a lower percentage opf peak loads on the pavement. These selected loads are unique for the vehicles and operational conditions used in the tyre load simulations.

Table 5.5: Selected tyre loads for static pavement response analysis.

	50th percentile	80th percentile	90th percentile	95th percentile
Tyre Load [kN]	21,3	23,8	24,4	33,6
Axle Load [kN]	85,2	95,2	97,6	134,4
E80 (n=4,0)	1,3	2,0	2,2	8,0

The intermediate pavement response analyses are performed to bridge the gap between the static (simple) pavement response analyses and the advanced finite element analyses. The main objective of these analyses is to incorporate the effects of vehicle speed and pavement mass inertia and damping in the pavement response analysis. The data for the intermediate pavement response analyses are based on the population of tyre load data simulated using the DADS software (Table 5.6). These tyre loads are used with the static response analysis method in Chapter 6, and correction factors applied to the calculated pavement response parameters to obtain the equivalent dynamic response parameters.

Table 5.6: Selected tyre loads for intermediate pavement response analysis (based on DADS generated tyre loads).

	50th percentile	80th percentile	90th percentile	95th percentile
Tyre Load [kN]	24,0	30,9	33,3	34,7
Axle Load [kN]	96,0	123,6	133,2	138,8
E80 (n=4,0)	2,1	5,7	7,7	9,1

In Figure 5.14 the cumulative tyre load distributions as generated using the DADS software (dynamic tyre loads) and the static tyre loads are shown. The selected tyre loads in Tables 5.5 and 5.6 originate from these data. The relationships between these data and the E80 tyre load, as well as the current legal axle load of 9 000 kg are also shown.

The static data indicates that above the 40th percentile (E80) and the 60th percentile (Legal load) the selected two loads are exceeded. In the case of the dynamic tyre loads, these limits are exceeded at the 30th (E80) and 38th (legal) percentiles. The reason for both the populations to exceed these limits lies in the fact that one third of the vehicles used in the simulations were 10 per cent overloaded, and one third were laden (100 per cent loaded). The reason for the dynamic tyre loads to be higher than the static tyre loads lies in the effect of the pavement roughness and vehicle speed on the vehicle-generated tyre loads. It thus indicates that using static tyre loads rather than actual (or dynamic) tyre loads would lead to using lower tyre loads in the pavement design than would be expected realistically on the pavement.

The data for the advanced pavement response analyses are typical load histories from the tyre loads. The data consist of tyre loads varying with increased time or distance intervals. These data are used in finite element analyses of the pavement response. For the purposes of this thesis the tyre load histories simulated using the DADS software are used.

To simplify the analyses and keep them comparable, the data from the left hand steer, first drive and first trail axle of each vehicle are used in the analyses. This results in 243 pavement response analyses using the advanced pavement response analyses method.

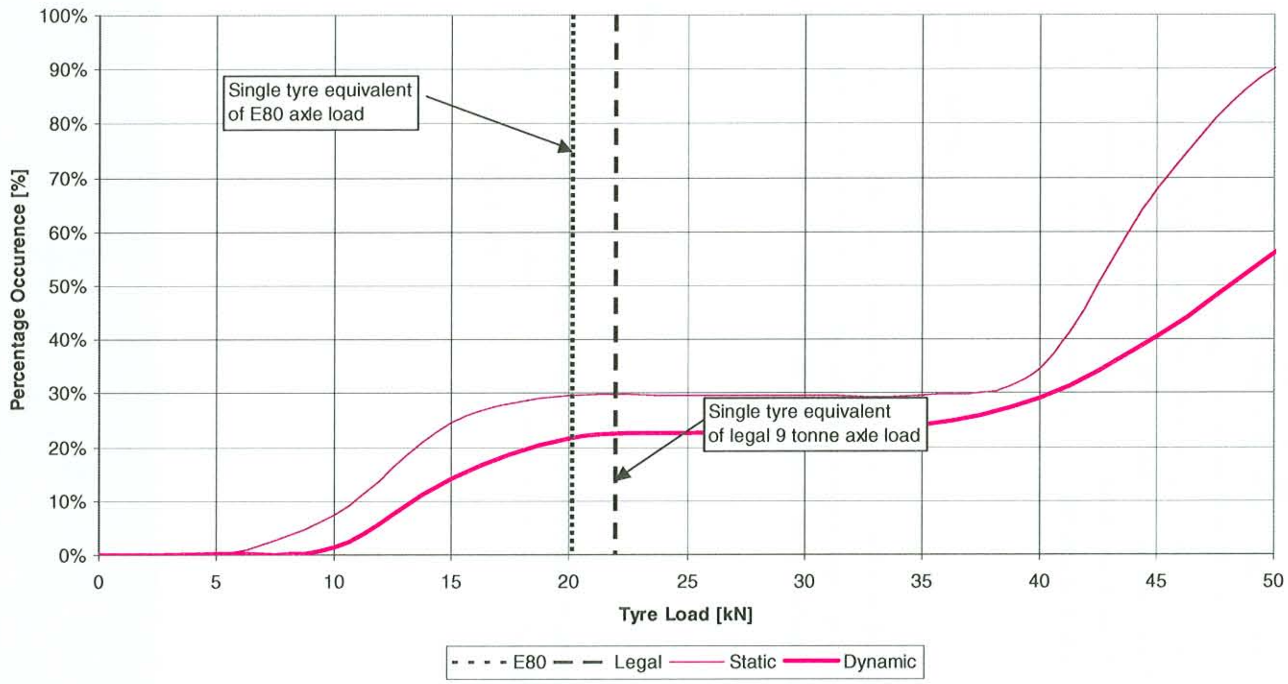


Figure 5.14: **Cumulative distribution of DADS-generated dynamic tyre loads and Static tyre loads from which the tyre loads for pavement response analysis in Tables 5.5 and 5.6 were selected, showing the relation to the E80 and legal tyre loads (data shown are for all vehicles and conditions simulated).**

5.7. Conclusions

The following conclusions are drawn based on the information and discussions in this chapter:

a. The average tyre load and DLC are functions of the actual load on the vehicle, while the standard deviation, CoV and range are functions of the vehicle speed and pavement roughness;
b. Statistically significant difference at the 95th per cent confidence level existed between the means, averages, standard deviations and distributions of most of the axle groups investigated;
c. The tyre loads on the left side of the vehicles (outer wheel track) were higher than those on the right side of the vehicle due to the camber of the pavement;
d. The DADS-simulated tyre loads were lower than the TFP-simulated tyre loads due to the lack of roll effects and the simplified models used in the TFP analyses;
e. The tyre load consists of a static and a dynamic load component;
f. The static load component is directly related to the GVM of the vehicles that use the pavement;
g. The dynamic load component is directly related to and dependent on the vehicle speed, vehicle type, GVM, load and pavement roughness;
h. The control of tyre load levels on roads is the joint responsibility of the road authority (through control of pavement roughness and vehicle speed) and the vehicle owner (through control of GVM and vehicle speed);
i. The main objective of optimising tyre loads is to keep the dynamic portion of the tyre load as small as possible;
j. Dynamic loads at ultra low frequencies (wavelengths > 100 m) are mainly related to the product of the GVM, pavement roughness and vehicle speed), while the dynamic loads at typical body bounce and axle hop frequencies (wavelengths < 100 m) are mainly related to the product of the pavement roughness, vehicle speed and vehicle type;
k. The tyre load distribution of a selection of vehicles can be described as normal, and
l. It is possible to develop tyre load distributions for use in pavement response analysis based on parameters such as the GVM, vehicle type, vehicle speed and pavement roughness.

5.8. Recommendations

The following recommendation is made based on the information and discussions in this chapter:

- Selected data from the full set of all the vehicles, speeds, loads and roughnesses are used in the pavement analyses in Chapter 6, as this would be realistically expected on a normal pavement.

5.9. References

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TRH4 see Structural design of flexible pavements for Interurban and rural roads.