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INCORPORATING MOVING DYNAMIC TYRE LOADS IN PAVEMENT DESIGN AND ANALYSIS

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INTRODUCTION

Current mechanistic pavement design and analysis techniques use several simplifications to enable the process to be practical and cost-effective. These include equivalent vehicle loads, linear elastic analysis and static vehicle load and pavement response analysis. These simplifications allow the process of pavement design and analysis to be applied by the majority of engineers, but do cause the process to be less realistic. In recent years attempts were made to incorporate more realistic effects into pavement design and analysis. These include incorporation of moving and moving dynamic vehicle loads, and dynamic pavement response effects.

In an ongoing research development, the CSIR is investigating the effects of moving dynamic loads and dynamic pavement response for typical South African conditions. The ultimate goal is to provide a relatively simple but accurate method for normal day-to-day use, incorporating these effects where necessary.

As part of the development of the analysis procedure, the aim of this paper is to present the dynamic vehicle and tyre load effects for incorporation into the analysis procedure. This is achieved by investigating tyre loads. Thereafter, fingerprinting of South African vehicles is discussed, followed by a discussion on the results of the simulated tyre loads of various vehicles. Current design loads are compared to the simulated loads, and proposals for incorporation of moving dynamic tyre loads into pavement design are made.

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[1] This paper is an extract of PhD studies being conducted at the University of Pretoria.

REAL LIFE TYRE LOADS

Characterisation

Pavement loading has been shown by various authors to be a dynamic (time-dependent) phenomenon (Divine, 1997; Cebon, 1999). A pavement experiences a vehicle as a moving, time-varying set of contact stresses applied at the pavement surface. These stresses are determined by the static load carried by each tyre, the dynamic variation in load at each tyre (as affected by the suspension and tyre characteristics), the nature of the pressure distribution arising from the total load applied to the surface under the tyre, and in-plane forces applied to the surface in the form of shear stresses (Gillespie et al, 1993). The dynamic load component has been shown to increase the static load component by between 5 and 50 percent, depending on factors such as the vehicle (and vehicle components) dynamic response, vehicle operating conditions and pavement roughness level. Dynamic load profiles for heavy vehicles are characterised by two distinct frequencies. Body bounce generally dominates the dynamic loading, and is mainly caused by the response of the sprung mass of the vehicle to the pavement roughness. Axle hop becomes more significant at higher vehicle speeds and higher pavement roughnesses, and is mainly caused by the reaction of the unsprung mass to pavement roughnesses (Gillespie, 1992).

Generically tyre loads vary in two distinct ways. The first is the variation of load between different vehicles and tyres travelling on a pavement, while the second is the varying loads applied by a specific tyre along the pavement. The first type of variation has traditionally been accommodated in pavement analysis through the use of equivalent load concepts. The second type of variation in loads is that caused by the pavement roughness-induced movement of the vehicle. This is traditionally termed dynamic pavement loading (Divine, 1997).

Tyre load definitions

Four types of tyre loading can be identified:

1.   A load that is independent of time and position (thus constant load magnitude) and the position is independent of time, is termed a *Static Load (SL)* (a parked vehicle);

2.   A load that is independent of time and position (thus constant load magnitude) but where the position is dependent of time, is termed a *Moving Constant Load (MCL)* (a typical Accelerated Pavement Testing device load (i.e. HVS Mark III));

3.   A load that is dependent of time and independent of position (thus the load magnitude changes according to a time-based function) and the position is independent of time, is termed a *Dynamic Load (DL)* (a Falling Weight Deflectometer (FWD)), and

4.   A load that is dependent of time and position (thus both the load magnitude and position changes according to a time-based function) and the position is dependent of time, is termed a *Moving Dynamic Load (MDL)* (a real vehicle driving on a real pavement).

Essentially real traffic cause either Static Loads or Moving Dynamic Loads, while Dynamic Loads and Moving Static Loads are mainly used in research to simplify the understanding of pavement response.

Fingerprinting of vehicles and loads

Current information regarding typical vehicle and pavement components in South Africa (fingerprinting) is needed to analyse dynamic loads properly. Fingerprint data typically originate from sources such as are the National Traffic Information System (NATIS), national and provincial pavement management system (PMS) databases, component manufacturers, fleet operators and various other publications citing statistics regarding vehicles and roads. Some difficulties in collecting this type of information should be appreciated. Component manufacturers and fleet operators are generally not willing to part with information they regard as strategic to their business. Trends and assumptions have to be used as input for these parameters. It is expensive in terms of money and manpower to sample vehicles to collect the information, and such samples are easily biased due to the location, season or conditions under which the sample is taken.

The main vehicle components identified for fingerprinting and discussed in this paper are the tyres, suspension, configuration and speed of the vehicle. Radial tyres are increasing in popularity in South Africa, with estimates ranging between 50 and 70 per cent of the heavy vehicle market (Barnard, 1997) and surveys indicating up to 95 per cent (SATMC, 1997) of heavy vehicle tyres on the road to be radial. The most popular heavy vehicle tyre size in South Africa is the 12R22.5 tyre size (50 to 59 per cent) followed by the 315/80R22.5 (19 to 27 per cent) (SATMC, 1997). Super single tyres make up between 0.8 and 2 per cent of the market (SATMC, 1997; Steyn and Fisher, 1997). Tyre inflation pressures for heavy vehicles in South Africa range between 150 and 1 000 kPa (Steyn and Fisher, 1997), where the 150 kPa tyre inflation pressure clearly reflects under-inflated tyres.

Steel suspension is mainly used in South Africa. The current air suspension usage is estimated to be between 5 and 20 per cent of all heavy vehicles, and to be limited mostly to special types of vehicles such as those conveying fragile goods (Campbell, 1997). Rigid, articulated and interlink vehicles constitute the three most popular vehicle classes in South Africa (approximately 80 per cent of heavy vehicles) (NAAMSA, 1998; Nordengen et al, 1995). Average speeds for heavy vehicles on national roads in South Africa are 79,9 km/h (standard deviation 10,2 km/h) (Bosman et al, 1995). This is related to the legal speed limit of 80 km/h for trucks on the 40 roads included in the fingerprinting.

Dynamic vehicle response simulations

Data of 3 vehicle types operated over 3 pavements at 3 speeds with 3 load levels were used to simulate dynamic tyre loads. A static approach, intermediate approach (Tire Force Prediction programme (TFP)) and a complicated approach (Dynamic Analysis and Design System (DADS) (DADS, 1997)) were used to obtain simulated tyre loads. Only tyre loads at constant speeds were evaluated. The three speeds used for the simulations relate to the maximum legal speed for most heavy vehicles (80 km/h), a slow speed (40 km/h) and an illegally high speed of 100 km/h. The three load conditions consisted of an empty load, a legal maximum load and a typical overload (10 per cent) equal to that found for typical South African conditions (Nordengen, 1999).

The pavement data used for the tyre load simulations consisted of the pavement profiles of three typical pavements. Typical national pavement roughnesses in South Africa were shown to be around 2,0 HRI (Half-car Roughness Index) (Kannemeyer, 1998). Three sections of roughness 1,2 HRI, 3,1 HRI and 5,3 HRI were used.

The dominant unit of load used is the load on a single tyre of the vehicle. This approach was selected as it is possible to calculate the loads on any combination of tyres and/or axles when the loads on single tyres are available.

Static versus dynamic tyre load populations

The tyre load data obtained from the simulations were characterised using both a statistical and a spectral approach. The statistical approach consisted of calculating various standard statistical parameters of the data sets. A typical cumulative distribution of tyre loads is shown in Figure 1. The static data, 10 per cent overloaded, high speed and high roughness data for a typical vehicle are shown. This indicates the relative effects of each of the three parameters investigated on the simulated tyre loads. Figure 1 is affected severely by the selection of only 3 load cases (empty, 100 per cent payload and 110 per cent payload). A smoother population would result from selecting a continuous range of payloads, as would be found in reality. Such a range of load options was not economically feasible for this project.

The spectral approach consisted of calculating the dominant frequencies present in the sets of vehicular load data, using the Power Spectral Density (PSD) approach. The energies for various frequency bands (calculated as the area under the PSD curve) were also calculated.

A typical PSD curve is shown in Figure 2 for simulated tyre loads. The axle hop and body bounce frequency ranges are shown. A typical dominant body bounce frequency is shown at a wavelength of approximately 21 m. The 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 confirmed this phenomenon.

Parameter effects on tyre load populations

The tyre load data obtained using the various simulations were analysed to determine how the data for the various tyres, axles and vehicles compared. Visual comparison of this data indicated:

- The average tyre loads decreased as the number of wheels 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 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 sample variance increased with increased vehicle speed;
- The Dynamic Load Coefficient (DLC) decreased with increased payload.
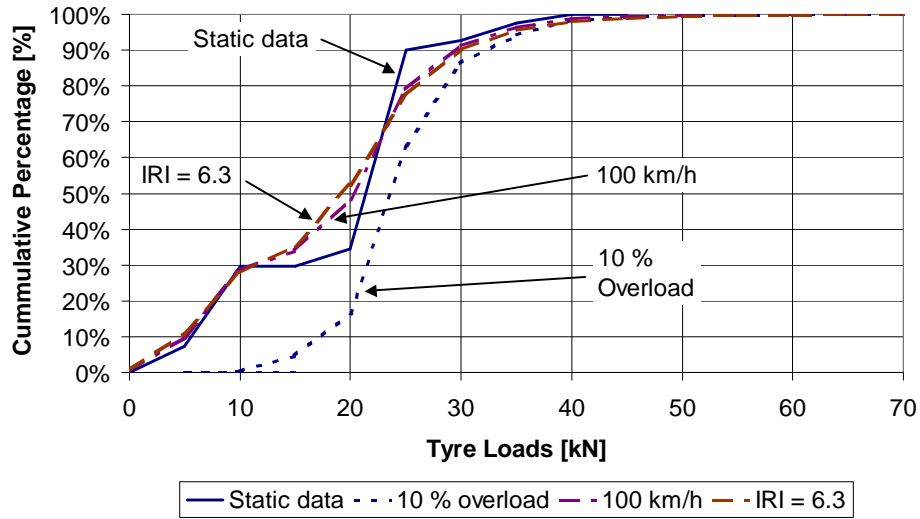
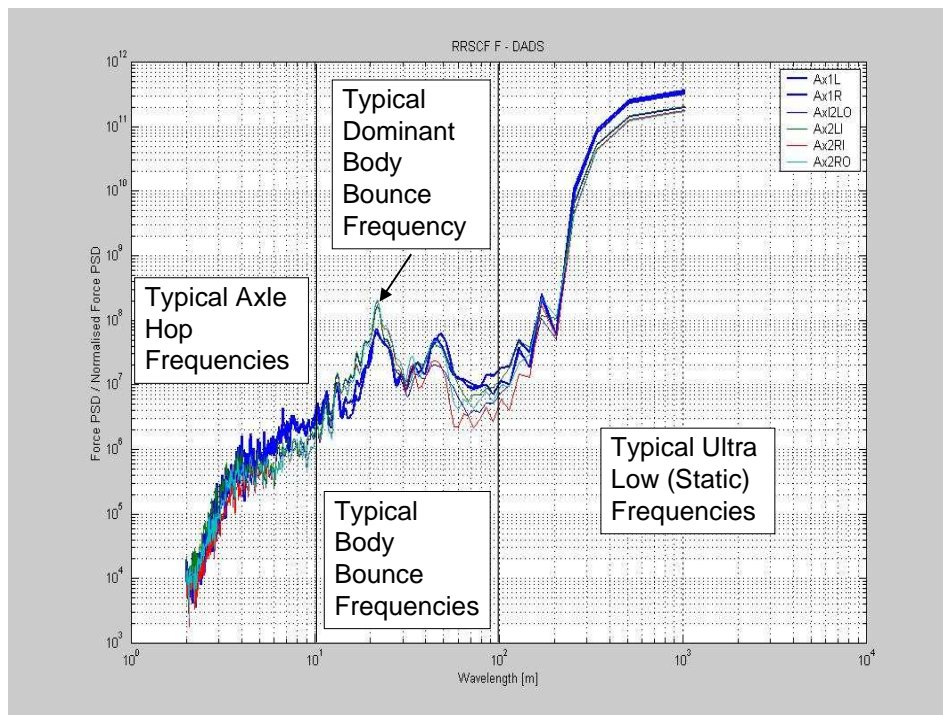Figure 1:   Cumulative distribution of tyre loads as simulated using DADS software.

Figure 2:   Typical Power Spectral Density (PSD) plot for tyre loads, indicating typical axle hop, body bounce and ultra low frequencies.

It thus appears that the average tyre load and DLC are functions of the actual load on the vehicle, while the standard deviation and sample variance are functions of the vehicle speed and pavement roughness.

Differences between the means, the standard deviations, the medians and the distributions of the data sets were analysed statistically. None of the groups of tyre load data compared had statistically significant differences in the groups themselves. Statistically significant differences with a confidence level of 95 per cent existed between most of the data sets. Most of the differences between the tyre loads on the steer/single, and the drive/trail and tandem/tridem axles groups lie in the fact that all the steer axles are single axles. These axles are less affected by the payload on the vehicle. The good 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 conditions investigated. The reason for the differences between the tyre loads on the left and right wheeltracks is the camber in the pavement that causes the left wheeltrack tyre loads to be higher than the right wheeltrack tyre loads.

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. The static data centred around the empty drive and trail axles (around 10 kN tyre loads) and the full and 10 per cent overloaded axles (around 25 kN tyre loads). The simulated dynamic load histories from the TFP and DADS simulations showed a higher standard deviation around these two data points than the static data. The effect of the dynamic component of the tyre loads is thus that the tyre loads are spread along a wider range than when only the static tyre loads are considered. Differences between the DADS- and TFP-simulated tyre loads mainly exist because of simplifications used in the TFP analysis.

Statistically significant differences existed between the tyre loads from the rigid, articulated and interlink vehicles. The data for the articulated and interlink vehicles are closer related than between the rigid vehicle and any of the other two vehicles. This may be because of the rigid vehicle having two single axles, and the articulated and interlink vehicles being combinations of truck-tractors and semi-trailers with tandem and tridem axles carrying the bulk of the payload. The GVMs of the articulated and interlink vehicles are also closer related to each other than to the rigid vehicle's GVM.

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

Typical body bounce frequencies of between 1,6 and 5,2 Hz, and axle hop frequencies of between 11,3 and 18,5 Hz were calculated for the various vehicles and conditions.

The data from the full data set containing all the tyres were used in further analyses. The reason for this decision is that the focus of the broader study is on a phenomenological and practical approach to incorporation of dynamic tyre loads in pavement design and analysis. In practice, the vehicle population deliver their loads to the pavement as single tyre units, and not as axle groups. It thus makes practical sense to analyse the effect of tyre loads on the pavement as the overall effect of the vehicle population.

Inferences

The average tyre loads are not affected statistically significantly by the pavement roughness or vehicle speed, but a high correlation (R^2 = 99,9 per cent, standard error of y-estimate = 97,1 N) was found between average tyre loads and Gross Vehicle Mass (GVM) per tyre. This is independent of the speed and pavement roughness. Conversely, the Coefficient of Variation (CoV) of the tyre loads shows good relationships (R^2 = 94,9 per cent, standard error of y-estimate = 0,055) with the vehicle speed, number of tyres per vehicle, pavement roughness, vehicle load (in terms of the percentage of full payload) and GVM.

The statistical analyses 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 be described as normal, as the reason for the skewness and kurtosis mostly lie in the fact that the data used in the analyses did not represent a continuous speed, load and/or roughness range. The vehicle payloads were especially a cause of skewness and kurtosis as only three load levels in this study. The main effect of variations in vehicle speed and pavement roughness on tyre loads, is directly proportional variations in the standard deviation of the tyre loads. Increases in any one or both of these two parameters (even with a constant GVM) cause a wider distribution of the tyre loads around the mean. The net result is that a higher proportion of peak loads are applied to the pavement. The effect of this is shown schematically in Figure 3. An increase in GVM will shift the whole distribution, but will have limited effect on the CoV.

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 road user. The road user is mainly responsible for the GVM of the vehicle, and also has control over the speed. *The road user influences 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 influences the standard deviation of tyre loads on the pavement by maintaining the pavement roughness at acceptable levels.* The dynamic component of the tyre loads is thus mainly influenced by the road owner. The road user may contribute to this influence by fitting more road-friendly suspensions (an aspect not covered in this paper) 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 4.

As the distribution of tyre loads is normal, the average and Coefficient of Variation of the tyre load population can be calculated for a given population of vehicles, speeds and pavement roughnesses. The expected distribution of dynamic tyre loads for this population can be calculated. The tyre load distribution developed can be used to select design loads at specified percentiles depending on the importance of the pavement. The equations for average and Coefficient of Variation are unique for the specific vehicle population and parameters used in their development.
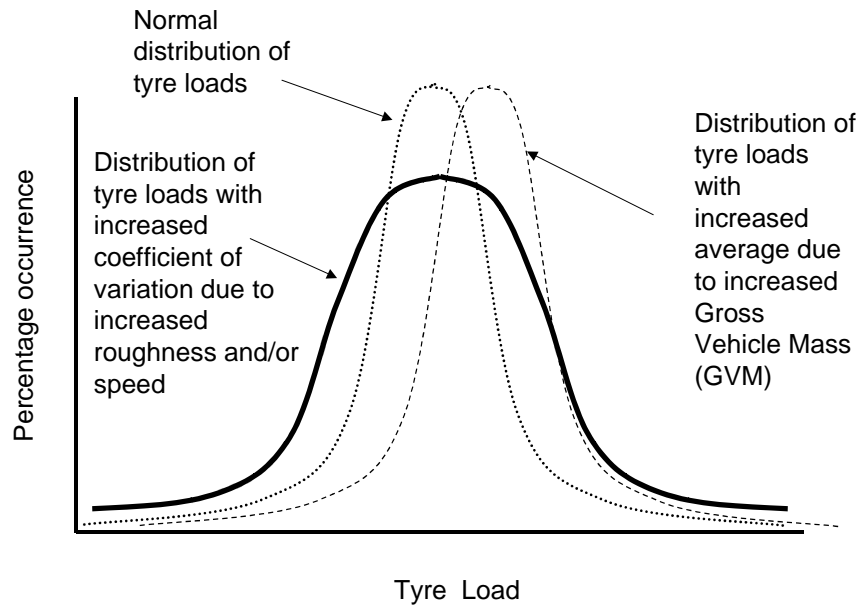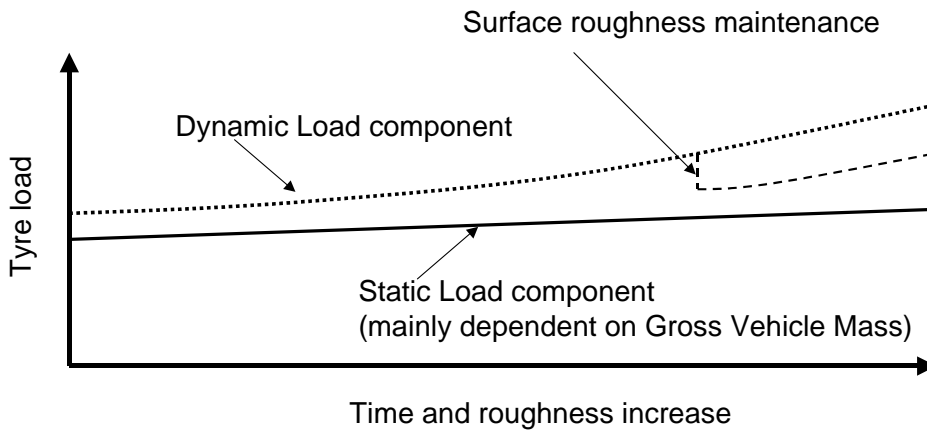
Normal
distribution of
tyre loads

Distribution of
tyre loads with
increased
coefficient of
variation due to
increased
roughness and/or
speed

Distribution of
tyre loads
with
increased
average due
to increased
Gross
Vehicle Mass
(GVM)

Percentage occurrence

Tyre Load

Figure 3:   Schematic histogram showing effects of changes in average and standard
             deviation of tyre loads.

Surface roughness maintenance

Dynamic Load component

Tyre load

Static Load component
(mainly dependent on Gross Vehicle Mass)

Time and roughness increase

Static Load component = f(Gross Vehicle Mass)
Dynamic Load component = f(Pavement roughness, Speed)

Figure 4:   Schematic indication of the static and dynamic components of vehicular load,
             and the effect of fitting more road-friendly suspensions and improvement of
             pavement surface roughness.

Analysis of the *spectral content* of the tyre loads indicated that the dynamic component of the vehicular loads (wavelengths < 100 m) is affected by the product of the pavement roughness, vehicle speed and vehicle type. The effect of this relationship is that although the average load on the pavement (GVM related) may stay constant, the dynamic components of the tyre load will increase due to increases in pavement roughness and/or speed. Pavement deterioration that cause pavement roughness increases, thus costs the road owner more through increased tyre loads. In Figure 4 these increases in tyre loads are shown, together with the anticipated effect of road maintenance on the tyre loads.

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).

LOADS USED IN PAVEMENT ANALYSIS

The current South African mechanistic Design Method (SAMDM) (Theyse et al, 1996) uses a static axle load (single axle, dual tyres) with a magnitude of 80 kN as the design load. There is no vehicle speed or pavement roughness effects accounted for in the analysis. This relates to tyre loads of 20 kN applied to the pavement. In Figure 5 the cumulative tyre load distributions as generated using the DADS software and the static tyre loads are shown. The relationships between these data and the E80 wheel load, as well as the current legal single axle load of 9 000 kg are 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 wheel loads, these limits are exceeded at the 30th (E80) and 38th (legal) percentiles. The reason for both the populations analysed 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 fully (100 per cent) loaded. The reason for the dynamic wheel loads to be higher than the static wheel loads lies in the effect of the pavement roughness and vehicle speed on the vehicle-generated wheel loads. It indicates that using static wheel loads rather than actual (or dynamic) wheel loads would lead to using lower wheel loads in the pavement design than would be expected realistically on the pavement.

IMPROVEMENTS IN PAVEMENT ANALYSIS THROUGH LOAD CHARACTERISATION

Improvements in the current SAMDM analysis method using load characterisation can be made at different levels of complexity. The first improvement is by using a selection of tyre loads based on the static load population for the population of vehicles expected on a pavement. This would enable more realistic tyre loads to be used in the analysis (refer to Figure 5). Such a set of data is shown in Table 1 for the vehicle population used in this project. Typical percentiles of 95, 90, 80 and 50 are shown in Table 1, together with the axle load (standard single axle with dual wheels), and the equivalent 80 kN value for the selected loads. Exponents of 2,0, 4,0 and 6,0 were used in converting the tyre loads to E80s. This approach would, however, not allow the inclusion of any of the vehicle speed and / or pavement roughness effects discussed in this paper.

A next level of complexity that can be used in load characterisation is to select the loads for use in the pavement analysis from the population of dynamic tyre loads (Table 1). This would enable the effects of vehicle speed and pavement roughness on tyre loads to be included in the pavement analysis. However, if these data were used in current linear elastic time

independent analysis routines, incorrect stresses and strains would be calculated. Research have shown that a pavement will react with decreased stresses and strains to loads applied at increased speeds, mainly due to the inertia of the pavement layers (Lourens, 1995).
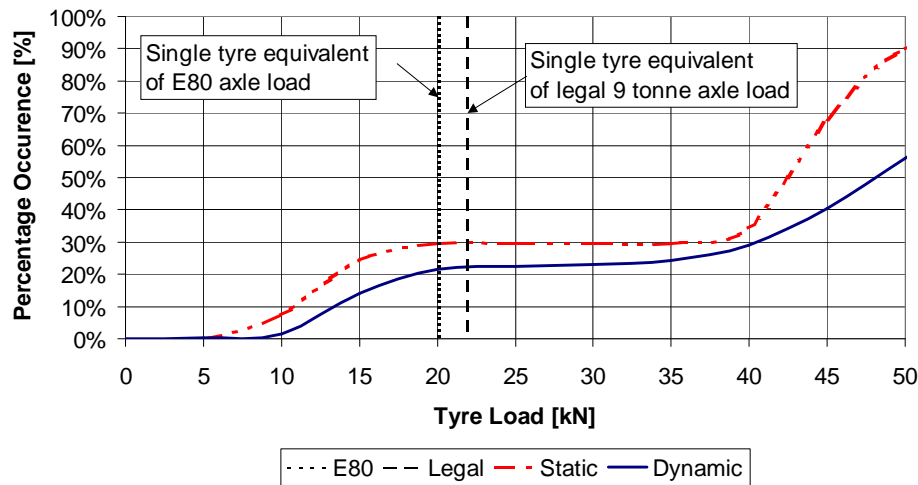

Figure 5:   Cumulative distribution of DADS-generated dynamic wheel loads and Static wheel loads showing the relation to the E80 and legal wheel loads.

As the pavement response parameters (stresses, strains and deflections) do not vary in the same way due to the effects of speed, the applied load cannot merely be adjusted for an analysis where the vehicle speed is incorporated into the analysis. The analysis (static response analysis) should still be performed using the static load case. A correction to obtain an 'equivalent dynamic response' from the static response analysis should then be applied to the specific pavement response parameters. This procedure will ensure that the applicable correction factor is applied to each of the pavement response parameters. Research to calculate the values of these factors for some typical South African pavements and load conditions is currently being finalised as part of the larger vehicle-pavement interaction project at the CSIR.

The best method for incorporating the effects of dynamic tyre loads into pavement analysis is to use tyre load histories varying with increased time or distance intervals as input data in finite element analyses of the pavement response. This enables the actual load history as well as the actual pavement response to be analysed much more accurately than with any of the other methods. It does, however, mean that the analyses are run at a much greater cost and the data needed for the analyses are also more costly. Currently, this application is seen as a research application to be used to develop better understanding of dynamic tyre loading and pavement response.

Table 1:   Selected vehicular loads for static pavement response analysis.

Static tyre loads				
	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=2, 4, 6)	1,1; 1,3; 1,5	1,4; 2,0; 2,8	1,5; 2,2; 3,3	2,8; 8,0; 22,5
Dynamic tyre loads				
Tyre load [kN]	24,0	30,9	33,3	34,7
Axle Load [kN]	96,0	123,6	133,2	138,8
E80 (n=2, 4, 6)	1,4; 2,1; 3,0	2,4; 5,7; 13,6	2,8; 7,7; 21,3	3,0; 9,1; 27,3

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn based on the information in this paper:

- The average tyre load and DLC are functions of the actual load on the vehicle, while the standard deviation and CoV are functions of the vehicle speed and pavement roughness;
- Statistically significant difference at the 95th per cent confidence level exist between the means, averages, standard deviations and distributions of most of the axle groups investigated;
- The tyre loads on the left wheeltrack were higher than those on the right wheeltrack due to the camber of the pavement;
- 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;
- The control of tyre load levels on roads is the joint responsibility of the road owner (through control of pavement roughness and vehicle speed) and the vehicle owner (through control of GVM and vehicle speed);
- The main objective of optimising vehicular loads is to keep the dynamic portion of the vehicular load as small as possible;
- The tyre load population of a selection of vehicles can be described as a normal distribution, and
- It is possible to develop tyre load populations based on parameters such as the GVM, vehicle type, vehicle speed and pavement roughness.

The following recommendations are made based on the information and discussions in this paper:

- Fingerprinting of South African vehicles and pavements should be performed on a regular basis to allow a better understanding of the components influencing vehicle-pavement interaction;

- The analyses described in this paper should be extended to include other types of suspension, as well as more load cases and operational conditions;
- The effect of inclusion of the moving dynamic load cases on different South African pavement structures should be evaluated.

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