Considerations of Vehicle-Pavement Interaction for Pavement Design

by

WYNAND JACOBUS VAN DER MERWE STEYN

A thesis submitted in partial fulfilment of
the requirements for the degree of

PHILOSOPHIAE DOCTOR (TRANSPORTATION ENGINEERING)

in the

FACULTY OF ENGINEERING, BUILT ENVIRONMENT AND INFORMATION TECHNOLOGY

UNIVERSITY OF PRETORIA

January 2001

THESIS SUMMARY

Considerations of Vehicle-Pavement Interaction for Pavement Design

by

Wynand Jacobus van der Merwe STEYN

Supervisor: Professor A.T. Visser
Department: Civil Engineering
University: University of Pretoria
Degree: Philosophiae Doctor (Transportation Engineering)

SUMMARY

Pavement structures consist of combinations of materials that react to vehicle loading in specific ways. Vehicle loading and pavement response are time-dependent dynamic phenomena. Due to various reasons pavements have traditionally been analysed assuming that the load input and pavement response are static time-independent parameters. Pavement engineers have long realised that this is not the actual situation, and various efforts into incorporating dynamic loading and transient pavement response were made. It has been shown internationally that vehicles exert a dynamically varying load on the pavement, with the load magnitude depending on input variables such as pavement profile and vehicle component characteristics. It is essential to determine the magnitude and characteristics of these effects to enable optimal pavement design.

This thesis focuses on providing practical guidelines to characterising vehicle-pavement interaction from a pavement design viewpoint. The objectives focus on provision of a systems framework populated with models and data for the analysis of the transient response of pavement structures to dynamic tyre loads. It contributes to the state of knowledge mainly in development of a method for predicting moving dynamic tyre loads based on vehicle and pavement parameters, development of a method for estimating dynamic pavement response parameters based on static pavement response parameters, definitions for vehicle-pavement interaction studies, and an improved understanding of the issues relevant to vehicle-pavement interaction from a pavement design viewpoint in South Africa.

The method for predicting moving dynamic tyre loads is based on the knowledge that tyre load populations form a normal distribution, and that the parameters of this distribution can be predicted based on certain vehicle and pavement properties. The method can be used to develop moving dynamic tyre load populations for existing pavements to aid in providing optimum managerial decisions on maintenance and rehabilitation options and strategies.

The method for estimating the dynamic pavement response parameters based on static pavement response parameters is based on empirical relationships between static and dynamic pavement response parameters. It provides a tool to evaluate the possible effects of load speed on the population of expected pavement bearing capacities for a pavement structure.

The analyses and discussions contained in this thesis add to the current knowledge of vehicle-pavement interaction from a pavement design viewpoint, by highlighting dominant issues in such analyses. The effect of inadequate pavement maintenance and the resultant effect of inadequate pavement smoothness on moving dynamic tyre loads necessitate a new appreciation of issues such as quality control and pavement management, to ensure prime pavement quality for the entire pavement life.

Although this thesis provides an improved understanding of vehicle-pavement interaction for pavement design, much still needs to be done to improve this understanding. The recommendations in this thesis should be taken further to ultimately aid in the economic development of South Africa by ensuring a high-quality pavement network.

KEYWORDS

vehicle-pavement interaction, pavement design, dynamic tyre load, transient pavement response, pavement roughness, component fingerprinting, terminology, guidelines, frequency analysis, vehicle-pavement interaction framework

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

SAMEVATTING VAN PROEFSKRIF

Beskouings oor Voertuig-Plaveisel Interaksie vir Plaveisel Ontwerp

deur

Wynand Jacobus van der Merwe STEYN

Promotor:	Professor A.T. Visser
Departement:	Siviele Ingenieurswese
Universiteit:	Universiteit van Pretoria
Graad:	Philosophiae Doctor (Vervoer Ingenieurswese)

SAMEVATTING

Plaveisel strukture bestaan uit kombinasies van materiale wat op 'n spesifieke wyse reageer op voertuig belasting. Voertuig belasting en plaveisel respons is tyd-afhanklike dinamiese verskynsels. As gevolg van verskeie redes is plaveisels tradisioneel geanaliseer met die aaname dat die las inset en plaveisel respons statiese tyd-onafhanklike veranderlikes is. Plaveisel ingenieurs het lank reeds besef dat dit nie werklik die geval is nie, en verskeie pogings is aangewend om dinamiese belastings en plaveisel respons in te skakel by plaveisel ontwerp. Dit is internasionaal aangedui dat voertuie 'n dinamies veranderende belasting op plaveisels toepas, met die las grootte wat van inset veranderlikes soos die plaveisel profiel en voertuig komponent eienskappe afhang. Dit is belangrik om die grootte en eienskappe van hierdie tendense te bepaal, om optimale plaveisel ontwerp te verseker.

Hierdie proefskrif fokus op die voorsiening van praktiese riglyne vir die karakterisering van voertuig-plaveisel interaksie vanaf 'n plaveisel ontwerp oogpunt. Die doelwitte fokus op die daarstelling van 'n stelsel raamwerk waarin modelle en data gevoeg is vir analise van die bewegende respons van plaveisel strukture as gevolg van dinamiese bandlaste. Dit dra hoofsaaklik by tot die huidige kennis deur die ontwikkeling van 'n metode vir die voorspelling van bewegende dinamiese bandlaste gebaseer op voertuig en plaveisel veranderlikes, die ontwikkeling van 'n metode vir die berekening van dinamiese plaveisel reaksie veranderlikes gebaseer op statiese plaveisel reaksie veranderlikes, definisies vir voertuig-plaveisel interaksie studies en 'n verbeterde insig oor vraagstukke wat betrekking het op voertuig-plaveisel interaksie vanaf 'n plaveisel ontwerp oogpunt in Suid Afrika.

Die metode vir voorspelling van bewegende dinamiese bandlaste is gebaseer op die kennis dat bandlas populasies 'n normaal verdeling volg, en dat die veranderlikes van sodanige verdeling voorspel kan word met behulp van sekere voertuig en plaveisel eienskappe. Die metode kan gebruik word om bewegende dinamiese bandlas populasies vir bestaande plaveisels te ontwikkel, sodat optimale bestuursbesluite oor onderhoud en rehabilitasie opsies en strategië geneem kan word.

Die metode vir beraming van dinamiese plaveisel reaksie veranderlikes vanaf statiese plaveisel reaksie veranderlikes is gebaseer op empiriese verwantskappe tussen statiese en dinamiese plaveisel respons veranderlikes. Dit verskaf 'n metode om die moontlike effekte van las spoed op die populasie van verwagte plaveisel kapasiteit vir 'n plaveisel struktuur te bepaal.

Die analises en besprekings in hierdie proefskrif dra by tot die huidige kennis oor voertuig-plaveisel interaksie vanaf 'n plaveisel ontwerps oogpunt, deur die klem op belangrike vraagstukke in sodanige analises. Die effek van onvoldoende plaveisel onderhoud en die gevolglike effek van onvoldoende plaveisel gelykheid op bewegende dinamiese bandlaste, noodsaak 'n nuwe waardering van sake soos kwaliteits kontrole en plaveisel bestuur, om sodoende uitstekende plaveisel kwaliteit vir die volle plaveisel leeftyd te verseker.

Alhoewel hierdie proefskrif 'n verbeterde insig oor voertuig-plaveisel interaksie vanaf 'n plaveisel ontwerp oogpunt verskaf, is baie werk nog nodig om hierdie insig verder te verbeter. Die aanbevelings in hierdie proefskrif behoort verder geneem te word om uiteindelik tot die ekonomiese ontwikkeling van Suid Afrika by te dra deur die versekering van 'n hoë kwaliteit plaveisel netwerk.

SLEUTELWOORDE

voertuig-plaveisel interaksie, plaveisel ontwerp, bewegende band laste, dinamiese plaveisel reaksie, plaveisel ongelykheid, komponent identifisering, terminologie, riglyne, frekwensie analise, voertuig-plaveisel interaksie raamwerk

Opgedra aan Anita en my ouers

Gee aandag, luister na wat ek sê, let op, luister na my woorde:
Hou 'n boer aan met ploeg as hy wil saai? Hou hy aan grond breek en vore trek?
As hy die grond gelyk gemaak het, saai hy mos swartkomyn en komyn, sit hy koring en gars in waar dit moet kom en spelt aan die kante.
Sy God leer hom en gee hom die kennis hoe om alles te doen soos dit hoort.
Swartkomyn word mos nie met 'n slee uitgedors of komyn met wawiele uitgetrap nie. Swartkomyn en komyn word met 'n stok uitgeslaan.
Graan word gemaal vir brood, maar 'n mens hou nie eindeloos aan om dit te laat trap deur wawiele en deur trekdiere tot dit fyn is nie.
Ook dit is iets wat van die Here die Almagtige af kom; kennis wat van Hom kom, is wonderbaar en laat alles voorspoedig verloop.

Jesaja 28: 23-29 (83 vertaling)

ACKNOWLEDGEMENTS

I would like to extend my gratitude and appreciation to the following persons and institutions who made valuable contributions towards the successful completion of this thesis:

Prof Alex Visser, my promoter for this thesis, for his interest, guidance and mentoring during this study.

Dr Morris de Beer, for the many discussions and guidance provided during the preparation of this thesis.

Mr Colin Fisher, for his valuable assistance in various analyses and the technical excellence with which he performed this.

The Division for Road and Transport Technology, and specially the previous director, Dr Hoffman Maree, and the current Director, Mr Phil Hendricks, my Programme Managers, Mr Chris Rust and Benoit Verhaeghe, and Project Manager, Dr Steve Kekwick, for the opportunities and positive attitude towards the work going into this thesis.

Dr Fritz Jooste, for his assistance and guidance in the finite element analyses performed for this thesis.

My many colleagues at the DRTT, especially Mr Wessel du Preez and Dr Chris Semmelink for their ongoing support, interest and motivation.

My dank en waardering aan my ouers, skoonouers, broers en susters wat my deur baie jare aangemoedig en ondersteun het in my studies.

In besonder my dank en waardering aan Anita, Wynand en Wikus vir julle geduld, belangstelling en aanmoediging, en dat julle my na dit alles nog steeds liefhet. Ek is nou regtig weer julle s'n.

My grootste dank aan die Drie-enige God, wat in Sy genade aan my die insig geskenk het om 'n deel van Sy skeppingsorde beter te verstaan.

CONSIDERATIONS OF VEHICLE-PAVEMENT INTERACTION FOR PAVEMENT DESIGN

TABLE OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AC - Continuously graded Asphalt layer (used to designate thin asphalt layer in this dissertation)
AASHTO - American Association of State Highway and Transportation Officials
c - cohesion
CBR - California Bearing Ratio
CSIR - Council for Scientific and Industrial Research
CSRA - Committee for State Roads Authorities
DADS - Dynamic Analysis and Design System
DL - Dynamic Load
DLC - Dynamic Load Coefficient
DPSD - Displacement Power Spectral Density
DRTT - Division for Roads and Transport Technology
E80 - Equivalent 80 kN axle load (dual wheels)
E_{eff} - Effective elastic modulus
E_h - Horizontal effective elastic modulus
E_v - Vertical effective elastic modulus
ELT - Effective Layer Thickness
MCL - Moving Constant Load
MDL - Moving Dynamic Load
HVS - Heavy Vehicle Simulator
OMC - Optimum Moisture Content
PADS - Pavement Analysis and Design Software
PSD - Power Spectral Density
SAMDM - South African Mechanistic Design Method
SL - Static Load
TFP - Tire Force Prediction programme
VRSPTA - Vehicle Road Surface Pressure Transducer Array
θ - Sum of the three principle stresses
φ - Angle of internal friction of pavement material
$\mu\varepsilon$ - micro strain
$\sigma_{1,2,3}$ - Principle stresses
σ_t - Tyre/pavement contact stress

1. INTRODUCTION

1.1 Introduction

Pavement structures consist of various natural and engineered materials that react to load input from vehicles in specific ways. As tyre loading is a time-dependent dynamic parameter, the response of the pavement system to the input is in reality time-dependent and transient.

Due to reasons such as lack of computational power, models and data, pavements have traditionally been analysed in a static mode, where it is assumed that the load input is a static time-independent parameter, and that the response of the pavement is also static and time-independent. Pavement engineers have long realised that this is not the ideal and actual situation, and various efforts into incorporating dynamic loading and transient pavement response were made.

Although different methods exist for incorporating moving dynamic tyre loads and transient pavement response into pavement design, these methods are not necessarily perfect and user-friendly. Limitations exist with regard to issues such as tyre load characterisation, material models, the ability (or lack of ability) to model non-symmetrical load conditions and the material properties to be used in the models. A need exists to provide a practical approach to transient pavement response analysis to real moving tyre loads.

1.2 Background

The purpose of pavement management is to ensure the lowest total cost of road transportation to society. Two sets of models are required to accomplish this. A set of models for determining the costs to society of different pavement conditions, for different traffic levels, traffic compositions and environments, and another set of models for predicting the future pavement condition as a function of traffic loading, climate, materials and maintenance are required. In addition a method for selecting the optimum combination of possible actions is required. A pavement's bearing capacity is not of immediate concern to a road user, but has an important influence on the rate at which the pavement deteriorates. If pavement engineering is to progress, theoretical models are certainly needed. However, the end goal of minimising the total cost to society (i.e. vehicle operating costs, user delay costs, accidents, noise, aesthetics etc) should not be forgotten. Although quantification of many of these costs is a political decision, the pavement engineer should develop the models to allow the politician to evaluate the consequences of his decisions (Ullidtz, 1997).

Most current pavement analysis, design and rehabilitation methods assume that the traffic using the pavement consists of vehicles running at static load levels, without allowance for variations in the load level along a specific road. Further, the interaction between tyre and pavement is not currently quantified. Therefore, the effect of dynamic loading (where a vehicle's load constantly varies due to internal (vehicular) and external (road roughness) inputs) is not incorporated in the design philosophy or practice.

It has been shown internationally that vehicles do not exert a constant load on a pavement, but a dynamically varying load, with the magnitude depending on various input variables such as pavement profile, tyre and suspension characteristics, vehicle speeds, etc (Divine, 1997; Cebon, 1999). To enable optimal pavement design it is essential to determine the magnitude and characteristics of these effects, and whether or not it has any effect on the pavement performance and behaviour.

Conversely, knowledge of the effect of pavement surfaces on vehicles can also assist vehicle designers in optimising vehicle designs. It has been shown internationally that the dynamic loading effects of different vehicles differ, and knowledge of the effect of these vehicles on the pavement can further assist road agencies to plan and legislate against overloading (Divine, 1997). Locally it has been shown that the contact stresses developed between tyres and the road surface vary considerably among different types of tyres and operating conditions (De Beer et al, 1997).

1.3 Problem Statement

Current pavement design and analysis methods are based on simplifying assumptions regarding traffic loading (i.e. static constant loads) and material characteristics (i.e. linear elasticity). These assumptions cause implicit analysis errors that affect the reliability of the pavement analysis and subsequently affect the cost of a pavement, as these implicit errors must be accommodated in the final product.

1.4 Objectives of Study

The primary objectives of this study are twofold:

a. To develop a practical systems framework to evaluate the various components in vehicle-pavement interaction, and
b. To develop and verify a practical approach for the analysis of the transient response of pavement structures to dynamic input loads where appropriate.

This thesis focuses on providing a **practical** guideline for evaluating vehicle-pavement interaction from a pavement design viewpoint.

1.5 Scope

The overall scope of this thesis is the field of vehicle-pavement interaction, focussing on the dynamic load and transient response of the system. It falls within the scope and extent of this study to:

a. Indicate the current understanding of vehicle-pavement interaction through a literature survey;
b. Develop a holistic systems framework combining the various components of vehicle-pavement interaction;
c. Populate the holistic framework with state-of-the-art available models, analysis techniques and data;
d. Improve the models and analysis techniques where necessary to provide more realistic modelling capabilities and,
e. Develop a practical approach for performing the transient pavement-structure analysis under appropriate conditions.

It falls outside the scope and extent of this study to:

a. Investigate and develop new models and techniques for the vehicle part of the vehicle-pavement interaction system;
b. Generate new data for evaluation with the model;
c. Develop transfer functions for linking the stress and strain output from the model with expected pavement lives and economic issues, and
d. Investigate the surfacing roughness-vehicle interaction.

1.6 Contribution to the State of Knowledge

Much work has already been done in the field of dynamic vehicle loading internationally. Major projects were launched by different organisations in which various aspects of dynamic loading and vehicle-pavement interaction have been measured and investigated, for example, Divine (1997).

Broadly the field of vehicle-pavement interaction needs research in various areas. These areas are both on the macro- (phenomenological) and micro-levels. On the micro-level the interaction between specific components needs investigation (i.e. tyre-pavement surfacing interaction). On the macro-level a phenomenological evaluation of the concept of vehicle-pavement interaction and the issues that need further detailed investigation are required.

It is the purpose of this study to contribute to the state of knowledge in terms of:

a. Establishment of a holistic system approach to vehicle-pavement interaction in which the connections between the various components are defined;
b. Provision of a simplified method for estimating the moving dynamic tyre load on a pavement, and
c. Provision of a practical approach to transient pavement-structure response analyses for evaluating specifically South African pavement structures.

It is the longer-term view of the author that, subsequent to this study further work will be needed to investigate various detailed component level interactions that may be identified as in need of research through this study.

1.7 Layout of Thesis

This thesis consists of eight chapters. The relationships between the various chapters are shown schematically in Figure 1.1.

The thesis starts with a short introduction to the background and context of this study (*Chapter 1*). This is followed by a literature study on the current knowledge and practices with regard to the vehicle-pavement interaction phenomenon, the various vehicle and pavement components, and typical South African vehicles and pavements (*Chapter 2*). The aim of this chapter is to indicate the currently available approaches and techniques and the major limitations in these. It forms the basis for the further developments in the thesis. In *Chapter 3* the study approach developed for the research performed for the thesis is presented. Here the issues on which attention is focussed in the thesis are highlighted, and the approach to investigation of these issues discussed.

In *Chapter 4* a holistic vehicle-pavement interaction framework is developed. In this system the components identified as vital for dynamic vehicle-pavement interaction analyses are incorporated, and some issues related to the accurate analysis of the system discussed.

In *Chapter 5* the tyre loads generated using the various software packages are evaluated, and inferences regarding tyre loads are made. A simplified approach for determining moving dynamic tyre load populations is developed. Load populations for the pavement response evaluations in Chapter 6 are developed.

Chapter 6 is devoted to an investigation of the transient response of pavement structures to vehicle loading. It is the aim of this chapter to investigate the analysis of vehicle pavement interaction in terms of static and quasi-transient modes, and to determine the differences in analysis outcome due to different approaches. Typical current South African pavements are evaluated for different vehicle inputs, to determine the specific vehicle and pavement components of essence in transient analyses for South African conditions. Practical guidelines for vehicle-pavement interaction for pavement design of South African pavement structures are finally developed (*Chapter 7*). Some unresolved issues are also discussed in Chapter 7.

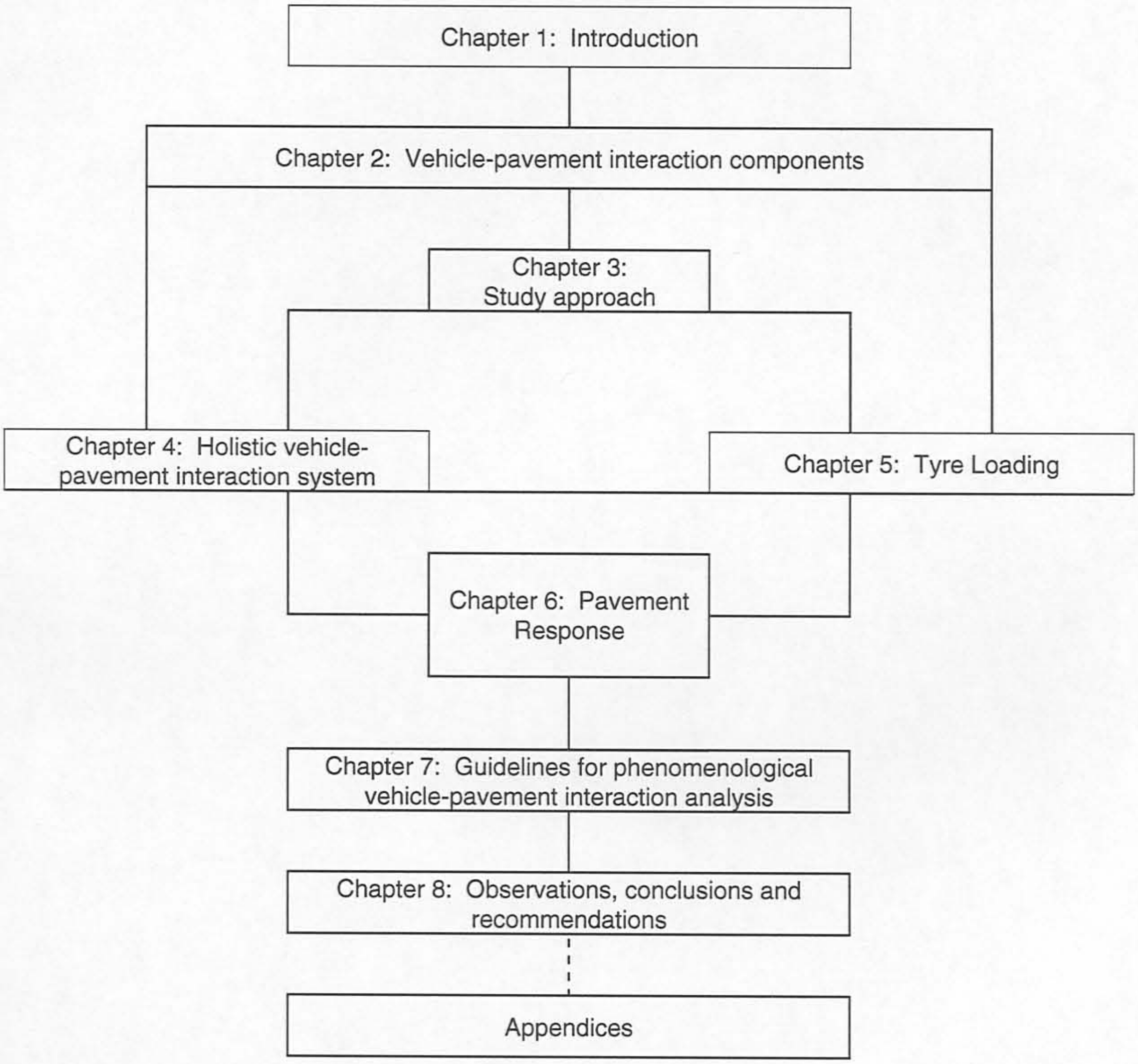


Figure 1.1: **Schematic layout of thesis.**

1.8 References

CEBON, D. 1999. **Handbook of Vehicle-Road Interaction.** Advances in Engineering 2, Lisse, The Netherlands: Swets & Zeitlinger.

DE BEER, M., FISHER, C. and JOOSTE, F.J. 1997. Determination of pneumatic tyre/pavement interface contact stresses under moving loads and some effects on pavements with thin asphalt surfacing layers. In: **8th International Conference on Asphalt Pavements;** (Proceedings of the 8th International Conference on Asphalt Pavements, held in Seattle, Washington, August 10-14 1997). Seattle, Washington.

DIVINE <u>see</u> **Dynamic Interaction of Vehicle & Infrastructure Experiment.**

Dynamic Interaction of Vehicle & Infrastructure Experiment: Asia-Pacific Concluding Conference. 1997. Melbourne, Australia: ARRB-TR.

ULLIDTZ, P. 1997. **Modelling flexible pavement response and performance.** Seattle, Washington: Instructor notes on nondestructive pavement analysis for the 8th International Conference on Asphalt Pavements Pre-Conference Technical Series.

2. VEHICLE-PAVEMENT INTERACTION CONCEPTS

2.1 Introduction

Chapter 2 consists of a literature review providing the currently available information for the five main themes addressed in this thesis. These five themes are: vehicle-pavement interaction systems, pavement roughness, vehicle components, pavement components, and vehicle and pavement fingerprinting. The focus on vehicle-pavement interaction systems and pavement components are more detailed than the other three themes as the bulk of the thesis focuses on these two themes. The other three themes are included as vital information from them is needed in the further analyses.

This thesis focuses on the primary transient response of flexible South African pavements to dynamic vehicle loads. It explicitly excludes transfer functions, economic models, pavement performance, rigid pavement response and bridge response.

2.2 Vehicle-Pavement Interaction Systems

2.2.1 Introduction

Systems methodology comprises the efficient planning, design and implementation of new systems, and the structuring of the state of knowledge or operational modelling of existing systems. A problem-solving process should provide for systematic incorporation of all the factors of interest, and should be a logical simulation of the progression of activities involved in efficiently solving the problem. The system should be clearly recognised and identified, to ensure clarity on inputs, objectives and constraints. A system consists of interacting components that are affected by external factors (Haas et al, 1994).

Vehicle-pavement interaction is the system in which the vehicle and the pavement exert mutual forces on each other. It should describe the vehicle and its components, the pavement and its components, and the way in which all of these components influence each other. This section focuses on the currently used vehicle-pavement interaction systems, and their dominant features and limitations.

2.2.2 Types of systems

Three viewpoints towards vehicle-pavement interaction covering the spectrum of available systems can be identified. These originate from the pavement management, vehicle engineering and combined pavement and vehicle engineering fields.

<u>Pavement management viewpoint</u>

This viewpoint has matured through years of development and is best described by Haas et al (1994). It was developed in response to the need to formulate the overall pavement problem in broad conceptual and theoretical terms that would enable the solution of a variety of pavement problems (Figure 2.1).

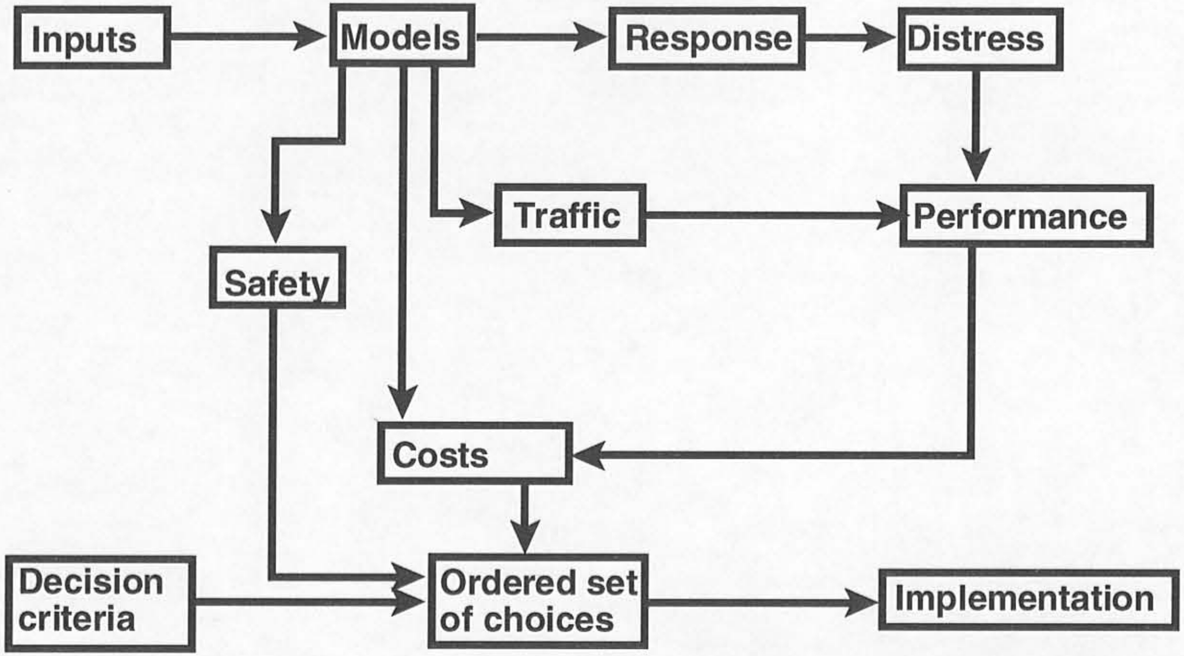


Figure 2.1: Pavement Management Systems (PMS) viewpoint to vehicle-pavement interaction (from Haas et al, 1994).

The system consists of eleven components. Four are essential to the vehicle-pavement interaction system, and the remaining seven complete the pavement management system. The four essential vehicle-pavement interaction components are the Inputs and Traffic (pavement and load variables), Models (defining vehicle and pavement reactions) and Response (pavement behaviour). The remaining seven components of Distress, Performance, Safety, Costs, Decision Criteria, Ordered set of choices and Implementation are not directly affected by the interaction between pavement and vehicle variables, but depend on the outcome of the response calculations. This system requires extensive input data to the various behavioural models. The primary response variables are evaluated using limiting and decision criteria, and after enough iterations to provide the required acceptability criteria, a final decision on the pavement design is made.

The dominant features of this viewpoint are its complete view of the overall pavement problem, including all possible input variables, a complete set of decision criteria and a modular approach towards behavioural models.

The main limitations of this viewpoint are the focus on pavement issues and the potentially complicated input data requirements for the behavioural and performance models.

Pavement engineering and the specific factors incorporated in either static or transient pavement analyses forms part of the general pavement management viewpoint. Currently the reaction of the vehicles to the pavement and the transient response of the pavement to tyre loads are generally not evaluated.

Collop and Cebon (1995a, 1995b) developed the Whole-Life Pavement Performance Model (WLPPM) and Ullidtz (1987; 1997) the Mathematical Model of Pavement Performance (MMOP). Both these systems are similar to the PMS viewpoint with slightly more explicit quantification of the interaction between vehicles and pavements. It does however focus on pavement performance issues, and will thus not be discussed in detail. De Pont et al (1998) indicated that the WLPPM provides the opportunity to experiment with different behavioural models within the existing pavement performance analysis framework.

Vehicle engineering viewpoint

This viewpoint is best described by Fancher and Gillespie (1997), Gillespie (1992) and Orr (1988). Vehicle engineers attempt to produce a product with unique advantages compared to other products on the road, while highway designers tend to encourage policies that promote roads with uniform characteristics for the level of service intended. Almost all trucks are different in terms of dimensions and axle loads. Highway laws and design standards have considerable influence on truck design, determining allowable limits on characteristics such as dimensions, loads and tyre tread width.

The weights and dimensions associated with a vehicle combination are the primary parameters by which acceptable vehicles are defined in road use laws. Vehicle-pavement interaction largely depends on the truck characteristics and operational conditions. It is vital to encourage evolution of both the pavement system and the truck transportation system toward ensuring better compatibility, particularly in matters of designing pavements to accommodate heavy vehicles, designing heavy vehicles to operate on those pavements and adopting policies that will lead to improved safety and efficiency of heavy vehicle transportation (Fancher and Gillespie, 1997).

Gillespie (1992) and Orr (1988) view the vehicle-pavement interaction system from a ride dynamic viewpoint, causing pavement roughness to be the only pavement parameter of importance, as this is one of the primary ride excitation sources. One of the main objectives of the vehicle engineer is to provide the driver, occupants and goods in a vehicle with as smooth a ride as possible. Therefore, the vibrations and dynamic response of the vehicle, caused by pavement roughness, is primarily a vehicle design and analysis parameter.

The dominant features of the vehicle engineers' viewpoint systems are the emphasis on the need for interaction between vehicle and pavement engineers, and the effect of pavement regulations on vehicle design. The limitation of these systems is the ignorance of pavement response issues.

Combined pavement and vehicle engineering viewpoint

In the DIVINE (Dynamic Interaction of Vehicles and Infrastructure Experiment) project the vehicle-infrastructure system was considered in an integrated way (Figure 2.2). The interaction between vehicles and pavements, and between vehicles and bridges has been separated, as different variables and mechanisms are at work. A full physical description of all the relationships involved is challenging, due to the complexity of the dynamic systems involved and the fact that some behaviours are spatially-related, some are time-related and some are cumulative with regard to repeated passes of the vehicle (Divine, 1997).

Pavement roughness initiates the vertical dynamics of the moving vehicle and the resulting dynamic tyre loads cause pavement responses that contribute to pavement distress. The pavement responses depend on the combination of dynamic tyre load, speed and local pavement strength, the depth at which the pavement response is measured, and the influence of the tyre contact patch in distributing the dynamic tyre load to the pavement structure. Over time and by repeated loading of heavy vehicles, the profile changes due to vertical surface deformations affecting the dynamic tyre loads. The pavement structural strength changes over time due to the accumulated effects of pavement responses as well as environmental influences. The net effect on pavement responses and distress will depend on the spatial relationship between dynamic tyre loads, pavement profile changes and pavement structural strength variations (Divine, 1997).

The dominant feature of this system is that it was developed together by a group of vehicle and pavement engineers and claim to incorporate all the relevant components. The main limitations of this system are caused by its completeness, as it requires relatively complicated input data and computational effort.

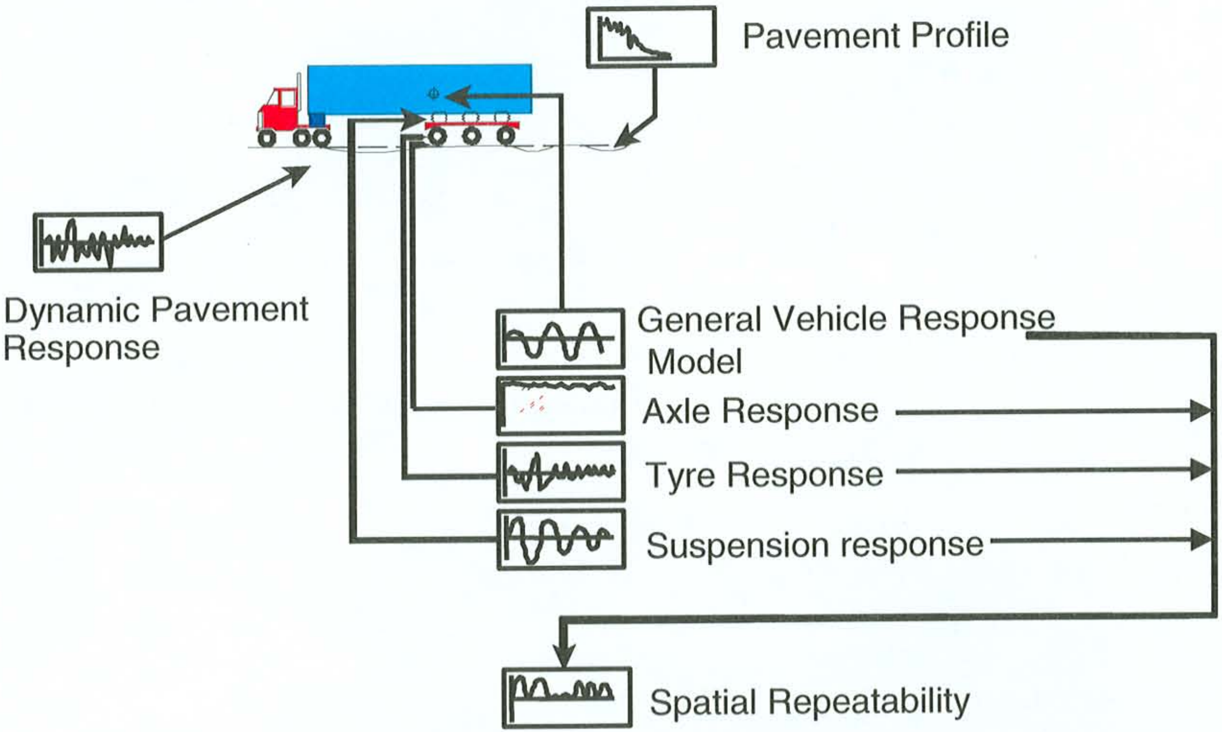


Figure 2.2: Divine approach to vehicle-pavement interaction (Divine, 1997).

2.2.3 Conclusions on vehicle-pavement interaction systems

The dominant features and limitations of the vehicle-pavement interaction systems originating from three viewpoints were discussed. Traditionally pavement and vehicle engineers both view the vehicle-pavement interaction system with bias towards their own knowledge and experience, and only through combined efforts such as DIVINE, and in areas such as the pavement management field, are attempts made to incorporate all the relevant components and interactions into the system.

The following general limitations were identified in most of the systems. A clear distinction does not exist between pavement behaviour and performance issues. It is further possible, due to the modular approach taken in most systems, to use behavioural models at various technology and/or complexity levels in the same analysis. The ultimate effect (beneficial or not) of such combinations is not clear (i.e. least denominator effect). These issues are addressed in Chapter 4.

2.3 Pavement Roughness

2.3.1 Introduction

The main cause of vehicle induced dynamic loading is the irregularities of the pavement surface (pavement roughness) (Gillespie, 1992). These irregularities cause an irregular input to the vehicle though the tyre-suspension combination. The response of the vehicle to these inputs constitutes the dynamic nature of vehicle loading. In this section pavement roughness definitions, models and data are investigated, specifically regarding the effect on heavy vehicle response.

2.3.2 Definitions and Concepts

Pavement roughness is defined as the variation in surface elevation that induces vibrations in traversing vehicles (Sayers et al, 1986a), or as " the deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic pavement loads, and drainage, for example, longitudinal profile, transverse profile and cross slope" (ASTM, 1996).

Frequency ranges for various surface characteristics are specified by the PIARC Technical Committee on Surface Characteristics. The roughness frequency range is that range which induces relative motion in road vehicle suspension systems over a reasonable range of operating speeds (McClean and Ramsay, 1996). The frequency range with wavelengths between 0,5 and 50 m is considered best to indicate pavement roughness.

Pavement roughness is one of the prime indicators of the deterioration of a pavement (Sayers et al, 1986b; TRH4, 1996). Roughness indices are used to have a simple value indicating the roughness level and trends in roughness level over time of a specific pavement. These indices are calculated from either the response of a roadmeter to the pavement roughness inputs, or using mathematical equations and measured pavement profiles.

Several roughness indices exist. They do not all measure roughness in the same way, and are not necessarily sensitive to the same types of roughnesses or applicable to the same conditions. The World Bank sponsored a major study of pavement roughness (the International Road Roughness Experiment (IRRE)) during which various methods for obtaining pavement roughness data, analysis of these data and presentation into standard formats were investigated (Sayers et al, 1986a; 1986b). The concept of the International Roughness Index (IRI) was consequently developed.

The IRI roughness scale best satisfied the criteria of being time-stable, transportable, relevant and readily measurable (Sayers et al, 1986a). It is a standardised roughness measurement related to the various response-type road roughness measurement systems (RTRRMS) with units of metre per kilometre (m/km) or millimetre per metre (mm/m). It is widely accepted as the index of choice for reporting pavement roughness. The IRI roughness scale is shown in Table 2.1 (Sayers et al, 1986b).

The true value of the IRI is obtained by obtaining a suitable accurate measurement of the profile of a wheeltrack, processing it through an algorithm that simulates the way a reference vehicle would respond to the roughness inputs, and accumulating the suspension travel. It is calculated at a standard speed of 80 km/h, as pavement roughness is dependent on vehicle speed (Sayers, 1995; Gillespie, 1992). IRI indicates the extent to which the surface of the pavement has deformed with respect to the specific wavelengths that affect the response of a specific vehicle travelling over the road (Mann et al, 1997).

The Half-car Roughness Index (HRI) is based on the same equations and assumptions as the IRI, but the average of the two wheeltracks are used in the calculation of the statistic. HRI is always less than or equal to the IRI calculation. IRI indicate vehicle response at the tyres, while HRI indicate vehicle response at the centre of the vehicle (Kannemeyer, 1997).

The IRI of two pavements may be similar although they have different roughnesses. This is possible if one pavement has more pronounced longer wavelengths and the other more pronounced shorter wavelengths, and both these bands fall into the IRI wavelength band (Mann et al, 1997).

IRI is particularly sensitive to shorter wavelengths associated with axle resonance, and longer wavelengths linked with body bounce. These wavelengths cause dynamic load variations that reduce the road holding ability of tyres and contribute to road damage caused by commercial vehicles (Mann et al, 1997). The IRI scale ignores wavelengths outside the 1.3 m to 30 m wavelength band since these do not contribute to the roughness experienced by road-using vehicles at speeds near 80 km/h (approximately 17 to 1,35 Hz) (Sayers et al, 1986a). The IRI is most sensitive to slope sinusoids with wavelengths of 15,4 and 2,3 m, with a gain of 1,5 and 1,65 respectively. The gain decreases to 0,5 for wavelengths of 30,3 and 1,3 m (Mann et al, 1997).

The concept of the Ride Number (RN) was developed to be a relevant (good correlation with other roughness indices), portable (ability of different profiling systems to obtain comparable values for similar profiles) and simple algorithm (Sayers and Karamihas, 1996).

Table 2.1: The IRI roughness scale (Sayers et al, 1986b).

IRI [mm/m]	Description	Airport Runways and Super Highways	New Pavements	Older Pavements	Maintained Unpaved Roads	Damaged Pavements	Rough Unpaved Roads	Normal Use
16	Erosion gulleys and deep depressions						▨	50 km/h
15							▨	
14							▨	
13							▨	
12	Frequent shallow depressions, some deep						▨	
11						▨	▨	60 km/h
10					▨	▨	▨	
9					▨	▨	▨	
8	Frequent minor depressions				▨	▨		
7					▨	▨		80 km/h
6				▨	▨	▨		
5	Surface imperfections			▨	▨			
4			▨	▨				100 km/h
3			▨	▨				
2	None	▨	▨					
1		▨						
0	Absolute perfection							

The IRI is not related to all vehicle response variables. It is most appropriate when a roughness measure is desired that relates to overall vehicle operating cost, overall riding quality and overall surface condition (Sayers and Karamihas, 1996). It is intended to reflect the pavement roughness attributes that affect the ride quality of passenger vehicles, and was not intended to describe the pavement roughness characteristics affecting heavy trucks, as is needed in this study. IRI does not show sensitivity to excitation frequencies as observed under heavy vehicle traffic (IRI sensitivity at 1,5 and 11 Hz, while heavy vehicle sensitivity at 3,5 and 12 Hz) (Papagiannakis and Gujarathi, 1995). Because of these different wavelengths affecting different vehicles, IRI is a poorer measure of ride quality for truck drivers than for car occupants. Trucks may be more sensitive to longer wavelengths inducing pitch and roll response modes (Mann et al, 1997; McLean and Ramsay, 1996).

Papagiannakis and Gujarathi (1995) described a pavement roughness statistic called Truck Response to Roughness Index (TRRI). The TRRI was developed to allow the roughness experienced by heavy vehicles to be expressed, allowing for the difference in dominant frequencies experienced by trucks and cars. TRRI is a frequency-domain calculation of the Root-Mean-Square acceleration of the frame of a reference truck. In Table 2.2 the IRI and TRRI values for two typical pavements are shown. It indicates that the difference between the two indices is not a constant, as the relative differences between the various parameters in the model cause the output to be dependent on the specific wavelengths present in the pavement profile analysed.

Table 2.2: IRI and TRRI values for two typical pavements (Kemp, 1997).

Pavement description	IRI [mm/m]	TRRI [m/s^2/m]	Percentage difference [%]
Very good	1,67	2,01	20,8
Good	2,68	3,31	23,8

A vehicle travelling on a pavement has two response modes. These are the body bounce at frequencies typically around 1 to 4 Hz, and the axle hop at frequencies around 10 to 18 Hz (Huhtala, 1995). Vehicle response to the pavement profile can be modelled in the frequency domain as a response function. The vehicle response characteristics amplify profile frequencies around the natural frequencies of the response modes, and attenuate profile frequencies well removed from those of the response modes. Mathematically, the vehicle frequency response function acts as a multiplier to the input road profile Power Spectral Density (PSD) to give the PSD of the vehicle response. For frequency characterisation of road profiles and frequency domain analysis of vehicle responses to the profile, the road profile can be characterised as a PSD. The PSD shows the variance in road profile elevation (or slope) as related to spatial frequency (McClean and Ramsay, 1996).

2.3.3 Pavement roughness input data

For this thesis, the actual pavement profile is of more importance than the roughness index, as the vehicle response models need actual pavement profiles as input. Various methods exist for measuring pavement roughness, depending on the objective and level of technology needed. The three main methods are panel ratings, response type road roughness measurements (RTRRMs), and profiling (Kannemeyer, 1997). Profiling is the best measurement method for use in vehicle-pavement interaction work, as this provides data to be used as input into vehicle-response models, and the spectral content of the pavement roughness can be calculated and used objectively in evaluation of the pavement.

In South Africa the High Speed Profilometer (HSP) is mainly used for pavement profile measurements. Rod-and-level equipment is generally more tedious than the HSP. The HSP measures the pavement profile at 80 km/h and a spatial frequency of 245 mm. These data are collected for two wheeltracks 1,6 m apart, with an accuracy of 0,26 mm. Currently there are approximately 7 770 km of historic data available, with more data being collected constantly (Kemp, 1997). Representative input data selected from these profiles are used in this thesis.

2.3.4 Conclusions

Pavement profile and roughness data are of vital importance to the analysis of vehicle-pavement interaction, as it provides the stimulus for dynamic pavement loading. Various pavement roughness indices are available, but the IRI is mostly accepted as a reference standard. The IRI is not as effective for analysing pavement roughness experienced by heavy vehicles, because the dominant frequencies experienced by cars and heavy vehicles differ. A different pavement roughness statistic (TRRI) is preferred to describe pavement roughness experienced by heavy vehicles.

Based on the information provided in this section, both the IRI and the TRRI are selected as indicators of pavement roughness. The IRI is used for comparison with existing databases, while the TRRI is used to indicate the roughness levels as experienced by heavy vehicles. The spectral content of pavement roughness is used where it can contribute to the understanding of specific vehicle responses. The input data for the vehicle response models are provided in terms of actual pavement profiles as measured with the HSP.

2.4 Vehicle Components

2.4.1 Introduction

This section focuses on vehicle components and models describing the response of vehicles and their components to external inputs. In the context of this thesis, the source of these external inputs is pavement roughness. Firstly, vehicle components and their critical parameters are identified. Next, vehicle models and response evaluation techniques are evaluated. Finally, some dynamic loading issues are discussed. Specific vehicle component characteristics typical for South African conditions (and used in this thesis) are summarised in Section 2.6.

2.4.2 Vehicle components

Vehicle components can be classified as sprung and unsprung masses. The sprung mass includes all parts supported by the suspension (including portions of the suspension members) while the unsprung mass includes all parts not carried by the suspension system, but supported directly by the tyre, and considered to move with it (Gillespie, 1992). The main vehicle components for discussion are the tyres, suspension, dimensions, configuration and load.

Tyres are important to pavements as they are the only contact point between the vehicle and the pavement and the point at which the actual distribution of contact stresses and load are conveyed to the pavement. Very little attention was traditionally given to tyres and their behaviour by pavement engineers.

The three basic functions of a tyre are to:

a. Support the vertical load while cushioning the vehicle against pavement shocks;
b. Develop longitudinal forces for acceleration and braking, and
c. Develop lateral forces for cornering (Gillespie, 1992).

Various combinations of tyre sizes and types are used on heavy vehicles. The main tyre types used are cross- and radial ply tyres. Truck tyres differ in width from 285 mm to 425 mm and diameter between 537 mm and 1 309 mm (SABS 1550, 1994). Normally tyres with widths of less than 315 mm are used as dual sets (except on steering axles) while those with widths of more than 315 mm can be used as single tyres (super singles).

Tyre characteristics depend on the construction of the tyre and the materials used. Tyre construction (i.e. radial or cross ply) affects the footprint and directional stability of the tyre, while different material compounds affect the way in which the tyre deforms and deteriorates (Gillespie, 1992). The main operational characteristic of tyres is the tyre inflation pressure. Specific tyre inflation pressures are recommended for use for specific tyres depending on the tyre construction, tyre load and tyre size (SABS 1550, 1994).

The contact stress distribution and magnitude between the tyre and the pavement surface is affected by parameters such as the tyre type, tyre inflation pressure, tyre load, tyre condition, speed and pavement condition (De Beer et al, 1997a). Different contact stress distributions are important for detailed tyre-pavement interaction studies. In this thesis only the maximum vertical contact stresses between the tyre and pavement are used as input parameter to the pavement structure.

Tyre models are used to describe the behaviour of tyres under operational conditions. The objectives of tyre models are to calculate the lateral forces on a tyre given certain operational characteristics (i.e. the vertical axle load, slip parameters, velocity and frictional pavement properties) (Preston, 1996). For the purposes of this thesis typical maximum vertical contact stresses (CS_{max}) as modelled using the relationships developed by De Beer et al (1997a) from Vertical Road-Surface Pressure Transducer Array (VRSPTA) data are used. The VRSPTA is used to measure tyre-pavement contact stresses in three dimensions. De Beer's approach appears the most suitable for further use in this thesis, because of its simplicity and the ability to provide vertical contact stress data without the need for complex input data. Equation 2-1 is used to calculate the maximum vertical contact stress peaks.

$$CS_{max} = 80{,}449 + 0{,}902TiP + 16{,}121\ Load$$

where :

CS_{max} – Maximum Contact Stress [kPa]

TiP – Tyre Inflation Pressure [kPa]

Load – Wheel Load [kN]

$R^2 = 92\%$

Std error = 138 kPa

Equation 2-1: Maximum vertical contact stress peaks

There are mainly two types of suspension used on heavy vehicles in South Africa. These are air suspension and steel suspension (Van Niekerk, 1992; Campbell, 1997). The operational characteristics of these two types of suspensions differ, resulting in different effects on pavement loads. The type of springs and dampers, together with the dynamic load sharing between tandem axles are of most significance to the dynamic interactions of the truck with the pavement (Gillespie et al, 1993).

The main functions of a suspension system are to connect the wheels to the vehicle frame, position the tyres on the road, ensure road contact during travelling, transmit drive, braking and turning forces and spring and shock absorber loads and isolate the vehicle from road induced vibrations (Limpert, 1982).

The main characteristics of suspension systems affecting their behaviour are the composite vertical and roll stiffnesses, and the damping (Pretorius, 1990). The composite vertical stiffness consists of the combined stiffnesses of the individual springs. The composite roll stiffness is a function of the individual spring rates, lateral spring spacing and any auxiliary roll stiffness, and indicates the resistance of the suspension to vehicle roll. Suspension damping is a combination of the Coulomb damping (originating from interleaf friction) and viscous damping (originating from shock absorbers). Spring properties are characterised by the force-deflection characteristics of the suspension system (Gillespie et al, 1993).

In the Divine (1997) experiment it was concluded that indications are that a vehicle equipped with air suspension may cause less damage to a pavement than the same vehicle equipped with steel suspension. The results are, however, not conclusive and dependent on factors such as the type of pavement, distress, and vehicle. A sprung mass frequency of 1.5 Hz, viscous damping of 20 per cent and Coulomb damping of less than 50 per cent of the viscous damping are desirable for road friendly suspensions. These conditions may be difficult to achieve with steel suspensions.

The general dimensions of a vehicle include the overall length of the combination of vehicles, the width of the vehicle, distances between the axles and distances between the tyres on an axle. Restrictions are normally placed on the dimensions of vehicles through the road regulations (Fancher and Gillespie, 1997; Pretorius, 1990). The main effect of dimensions on vehicle-pavement interaction lies in the intervals between load applications from the various axles, and the percentage of load spread to each of the axles. These intervals are influenced by the speed at which the vehicle travels. It influences the load application frequency and therefore also the pavement response characteristics (Pretorius, 1990; Gillespie et al, 1993).

The configuration of a vehicle indicates the combination of components such as a truck/tractor and trailer. Although many combinations of components and vehicles are possible, industry makes use of a few optimum configurations. These are normally the configurations providing the most economical payload options within the framework of the allowed axle load regulations (Fancher and Gillespie, 1997). One of the systems used in South Africa for indicating vehicle configuration incorporates the number of axles on the vehicle and in each axle group (Nordengen et al, 1995). No indication is given of the tyre types and sizes, or physical dimensions of the vehicle.

The main effect of different vehicle and axle configurations on pavements lies in the effect that the specific combination of axles, and dimensions between axles, have on the response of the pavement.

The vehicle load is the primary vehicle component traditionally considered by pavement engineers. This is also one of the main vehicle parameters regulated through the maximum allowable axle loads. Studies have shown that fatigue of flexible pavement is highly dependent on individual axle loads while gross weight governs rutting for thicker (50 to 150 mm) asphalt surfacings (Gillespie et al, 1993). Load positioning on the vehicle and between axles and sides of the vehicle will affect the centre of gravity of the vehicle, which again is an important factor in the dynamic response of the vehicle.

2.4.3 Vehicle models

Todd and Kulakowski (1989) indicated analytical, experimental and computer simulations as three research methods that can be used for examining truck dynamics. Analytical methods are not practical due to the complexity of the mathematical models involved, while experimental methods are costly and limited by safety requirements. The most successful approach is to conduct a limited number of field tests to provide actual truck performance data to validate computer simulation programs. These computer simulation programs are used to extrapolate the experimental results over the range of test conditions where experimentation would be too dangerous or expensive.

Various vehicle models can be used for vehicle response to pavement roughness calculations. The simpler models consist of either quarter-vehicle or half-vehicle simplifications of the vehicle and can often be used with good effect (TFP; Macadam et al, 1980; Todd and Kulakowski, 1989). These models require less input data and computational effort, but their results may not be as accurate as the more complex models. The components are usually defined as part of the whole system, and only their characteristics can be changed and not their physical models.

The more complicated vehicle models allow for interchangeable component models and user-defined operating conditions, but are more expensive to develop, validate and use than the simpler models (DADS, 1997). It does, however, make good research sense to use these advanced models as reference models and use the most accurate simpler models to do production analyses. This approach is adopted in this thesis and thus a more advanced model (the reference model) and a simpler model (the production model) are identified.

The advanced vehicle model used is closely linked to the specific software used. In these advanced models the vehicle components can be modelled individually and these models combined to form a mathematical vehicle model. With the pavement profile as input to this mathematical model, the various response modes of the vehicle (i.e. roll, pitch and yaw) and the tyre loads at specific positions and time intervals, can be calculated (DADS, 1997). A typical vehicle model using the more advanced approach is shown in Figure 2.3.

Various programs exist for performing advanced vehicle-response calculations. Some of these are DADS (DADS, 1997), MADYMO (Jansen et al, 1996) and AUTOSIM (Sayers, 1991a; 1991b). All these programs have unique features and component models. As the focus of this thesis is on pavement response, a program was selected by evaluating the various programs on their published performance, locating a partner who owns one of the programs found suitable for the analysis, and co-operation with the partner on the detailed vehicle response analyses. Such a partner was found in Reumech Ermetek, who currently owns a copy of DADS, has extensive experience in the use of the program, and has validated the response of the program with real conditions and found it satisfactory (Nell, 1998).

DADS (DADS, 1997) is a computer simulation tool that is used to predict the behaviour of single or multibody mechanical systems. The mechanical model is analysed and position, velocity, acceleration and reaction forces are predicted for all parts of the model. Analyses can be performed in static, kinematic or dynamic modes. An advanced tyre module based on the Magic Tyre Formula is available in DADS. The standard tyre force elements calculate the normal, longitudinal and lateral tyre forces in the tyre-ground interface plane.

Most of the simpler vehicle response models use a simplification of the vehicle as a sprung and unsprung mass (or masses) connected via various springs and dashpots (TFP; Todd and Kulakowski, 1989). A typical half-vehicle simulation model is shown in Figure 2.4.

The Tyre Force Prediction Program (TFP) and PHASE4 (Macadam et al, 1980) programs are typical programs for the analysis of simple vehicle response simulations. PHASE4 is a time-domain mathematical simulation of a truck-tractor, a semi-trailer and up to two full trailers. TFP (TFP) is an analytical model of a truck or truck-tractor and semi-trailer combination used to predict the forces that occur between the tyres of the vehicle and the road. The program is similar to PHASE4, except that vehicle response is simulated at constant speed, and no turning or braking manoeuvres or roll effects can be simulated. It is only a two-dimensional vehicle model. Both programs have been used for many studies available in the literature on vehicle-pavement interaction (Van Niekerk, 1992).

Van Niekerk (1992) evaluated both TFP and PHASE4 for use in simulations of dynamic vehicle loading. Both were found to provide satisfactory results. TFP (which requires simpler input data) results were subsequently compared with measured dynamic load data and it gave a reasonable indication of the overall trend of the dynamic axle masses.

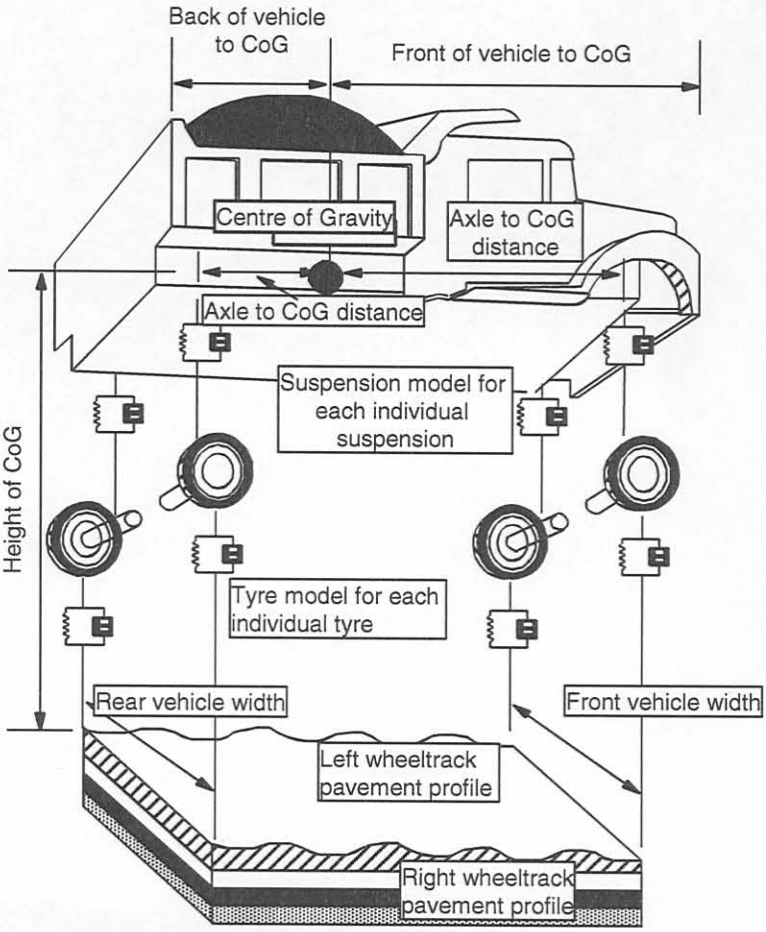


Figure 2.3: **Typical complex vehicle model indicating characteristics defined for all components (Sousa et al, 1988).**

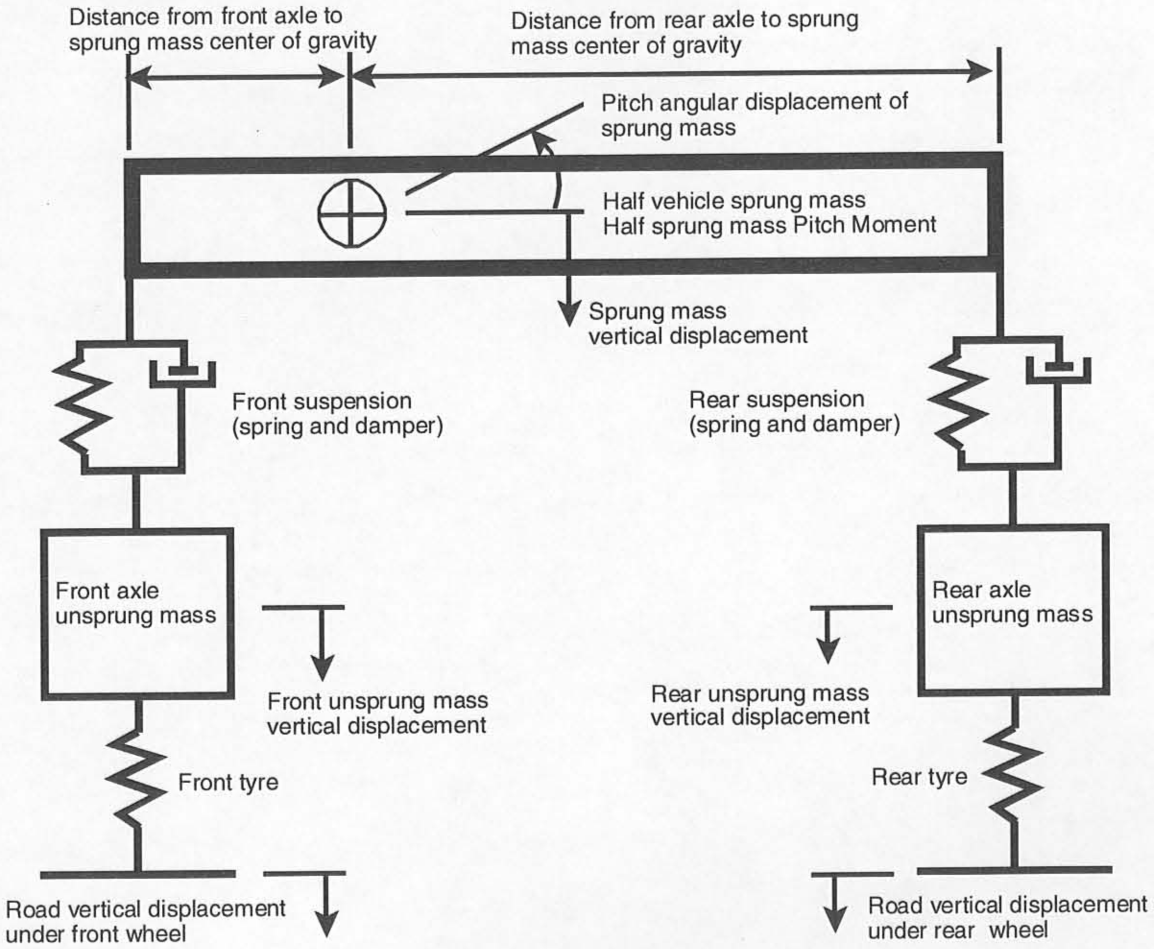


Figure 2.4: **Typical simple vehicle simulation model (Todd and Kulakowski, 1989).**

Kenis and Hammouda (1996) indicated through a sensitivity study of three truck dynamic simulation programs that vehicle roll plays an insignificant role in dynamic tyre force calculations, and that a pitch-bounce model is sufficient for most applications.

TFP was selected for use in this thesis as it provides all the information required for the simpler vehicle response program, and is computationally friendlier and requires less input data than PHASE4. DADS was selected as the reference vehicle response program.

2.4.4 Dynamic tyre loading

Pavement loading has been shown by various authors to be a dynamic (time-dependent) phenomenon (Divine, 1997). A pavement experiences a truck 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 be between 5 and 50 percent of the static load component, depending on factors such as the vehicle (and vehicle components) dynamic response, vehicle operating conditions and pavement roughness level.

The dynamic load effect of an axle is typically expressed as the Dynamic Load Coefficient (DLC) (Equation 2-2) or the Dynamic Stress Coefficient (DSC) (Equation 2-3). DLC indicates the Coefficient of Variance (CoV) of the applied variable load while DSC indicates the CoV of the stress measured at a specific position in the pavement structure (Sweatman, 1983; Kenis et al, 1997). Typical DLC values range between 0,01 and 0,40, while typical DSC values range between 0,03 and 0,22 (Kenis et al, 1997; Sweatman, 1983; Divine, 1997).

$$\text{DLC} = \frac{\text{std Load}}{\text{avg Load}}$$

Equation 2-2: Dynamic Load Coefficient.

$$\text{DSC} = \frac{\text{std } \varepsilon}{\text{avg } \varepsilon}$$

where

std Load – standard deviation of wheel force distributi on
std ε – standard deviation of strain history
avg Load – average wheel force
avg ε – average of strain history

Equation 2-3: Dynamic Stress Coefficient.

Dynamic load profiles for all heavy vehicles are characterised by two distinct frequencies. Body bounce (1.5 to 4 Hz) 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 (8 to 15 Hz) 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. The main cause for the dominating effect of the body bounce component may lie in the load ratio of approximately 10:1 between the sprung mass and the unsprung mass (Gillespie, 1992).

Two types of variability exist in pavement loading. These are the longitudinal loading variability and the cyclic variable load on a discrete point of the pavement (Divine, 1997; O'Reilly and Brown, 1991). While body bounce and axle hop frequencies characterise the longitudinal load profile, the cyclic variable load frequency depends on the speed and tyre patch length. For practical reasons the shortest discrete loading point can be defined as one tyre patch length. This causes typical load frequencies of between 18 Hz and 92 Hz (for a 300 mm tyre patch length and speeds of 20 km/h and 100 km/h).

Schematically the difference between the dynamic loading as experienced by the vehicle (longitudinal load variable) and the cyclic variable loading as experienced by the pavement on a discrete location can be described as in Figure 2.5. The y-axis indicates the actual load value, and on the x-axis time as experienced by the vehicle and the pavement is shown. The load history as experienced by the vehicle is continuous at body bounce and axle hop frequencies. The transient pavement load history is cyclic with frequency dependent on the vehicle speed and distances between axles and vehicles. Chatti et al (1995) indicated that use of a stationary pulse to model dynamic loading on a discrete point is insufficient to model the dynamic load effect. Mamlouk (1987) indicated that axle loads cause a series of half sine wave stresses in a pavement.

It is the opinion of the author that the dynamic loading effect could be analysed as two distinct but related processes. The primary load mode is the cyclic (transient) load on the discrete pavement position caused by the specific load generated at the specific point. The secondary load mode is the loads caused on the remainder of the pavement by the vehicle as it travels before and after the discrete point under investigation, and which is transferred to the discrete point under investigation via waves in the pavement. The relative importance of these two load modes depends on factors such as the variability of the load, the response characteristics of the pavement (i.e. damping), and the specific materials encountered. This opinion receives further attention later in this thesis. One of the alternatives proposed to simplify the analysis procedure is to neglect the effect of the secondary load mode.

Le Blanc and Woodrooffe (1995) defined spatial repeatability as the tendency for tyre load signals to have the peaks and lows to generally recur at the same locations on the pavement. This may either be caused by similar or different vehicles. Correlation coefficients of between 0.2 and 0.5 indicate moderate correlation, with higher coefficients indicating good spatial repeatability. Spatial repeatability specifically affects the cyclic damage variation on discrete locations, as it causes accumulation of increased damage on specific points.

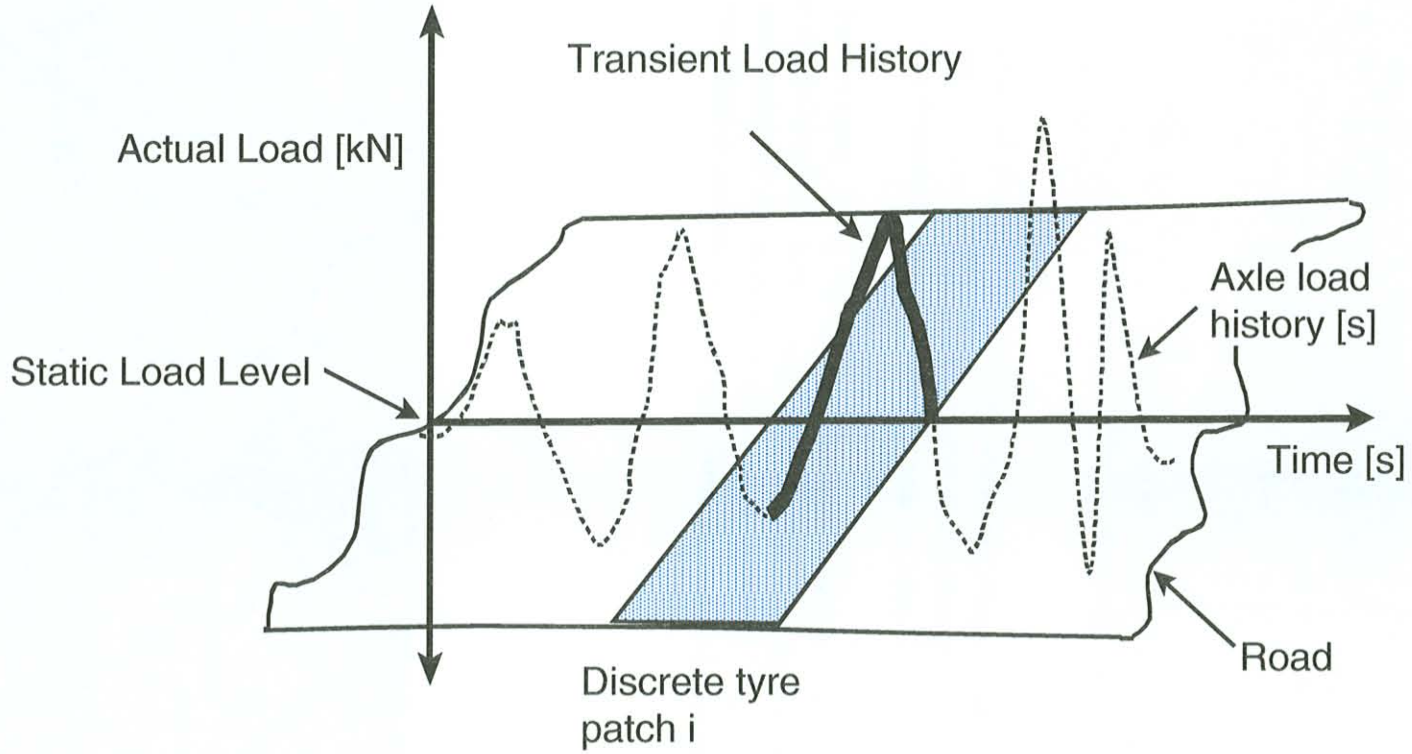


Figure 2.5: **Longitudinal axle load history and transient load history.**

2.4.5 Conclusions

The vehicle components of importance to vehicle-pavement interaction, specifically for linear constant-speed movement, were investigated in this section. The objective was to provide the necessary understanding, tools and data to enable calculation of vertical dynamic pavement-roughness-induced vehicle loads on pavements.

The main vehicle components identified are the tyres, suspension, dimensions, configuration and load of the vehicle. Standard parameters of each of these components were identified.

It was shown that vehicle models and evaluation techniques could be either detailed and complicated, or simple. DADS was selected as the reference vehicle model and evaluation technique for bench marking the simpler TFP program, selected for production analyses.

Dynamic pavement loading consists of two phases. The primary phase is the load effect on a discrete position of the pavement while the second phase is the load effect caused by the time-history of the vehicle away from the discrete point under investigation.

2.5 Pavement Components

2.5.1 Introduction

Pavement response constitutes the main part of this thesis. This is specifically with regard to the transient response of a pavement structure to a dynamic load input. The static response of a pavement structure and the static load input to a pavement are regarded as special cases of the general dynamic load and transient response model of the pavement structure.

Structural models for analysis of pavement response to traffic loads range in complexity from simple empirical models to sophisticated models that attempt to realistically describe the behaviour of the materials. The selection of the type of model depends on the ability of the designer to quantify the required material inputs and interpret the results of the models (Haas et al, 1994).

Desai and Gallagher (1984) stated that a valid solution to a problem in soil mechanics (of which pavement engineering can be seen as a specific branch) must satisfy the following three basic equations:

a. Equations of equilibrium (of stresses and forces) (Timoshenko and Goodier, 1951);
b. Equations of compatibility (of strains and displacements), and
c. Constitutive equations (or the relations between stresses and strains in the material).

This section starts with a discussion of the material models (constitutive equations) for the typical South African pavement construction materials used in this thesis, followed by models and techniques for the description of transient pavement structure response. Finally, the dynamic effects of vehicles on transient pavement structure response are discussed.

2.5.2 Materials

The main materials used in flexible pavement structures in South Africa are discussed in TRH14 (1985). Each of these materials reacts uniquely to external loads and environmental changes. In this section the typical constitutive equations and properties for seven of the materials identified for further use in this thesis in Section 2.6 are discussed. The eighth material, a double seal, does not posses any structural properties and is thus ignored for the analyses. The seven materials can be grouped into four groups. These are:

a. Thin (< 50 mm) asphalt (AC);
b. Granular materials (G1, G4, G6);
c. Cemented materials(C3, C4), and
d. Soils (SG1).

The load-response characteristics of materials for application in mechanistic models define their constitutive equations. Mechanistic material evaluation requires a compromise between complexity of testing and analytical procedures and the ability to perform tests cost-effectively under simulated field-conditions (Haas et al, 1994). Various generic material response models exist. Yoder and Witczak (1975) have shown three properties of materials to be sufficient to describe material behaviour needed for pavement analysis:

a. The stress-strain function (linear or non-linear);
b. The time-dependency of strain for given constant stress (viscosity), and
c. The strain recovery after stress removal (elasticity or plasticity).

These three properties are schematically shown in Figure 2.6. Various combinations of these three properties are possible to describe material response.

Asphalt materials typically show visco-elastic or elasto-visco-plastic behaviour (Motrescu and Visser, 1995). The mechanical models of visco-elastic behaviour include the common Maxwell, Kelvin, Burgers and Generalised models. Jooste (1997) effectively used the Burgers model for the analysis of visco-elastic behaviour of asphalt materials, to model the strain behaviour of asphalt under both laboratory and pavement loading conditions. The typical Burgers model is shown in Equation 2-4.

$$\varepsilon(t)=\frac{\sigma}{E_1}+\frac{\sigma t}{\eta_1}+\frac{\sigma}{E_2}\left[1-e^{(-tE2/\eta2)}\right]$$

where

ε – strain (time dependent)
σ – applied stress [MPa]
E – elastic modulus of spring [MPa]
η – coulomb damping factor [MPa.s]
t – time [s]

Equation 2-4: Burgers model for visco-elastic behaviour in asphalt (Jooste, 1997).

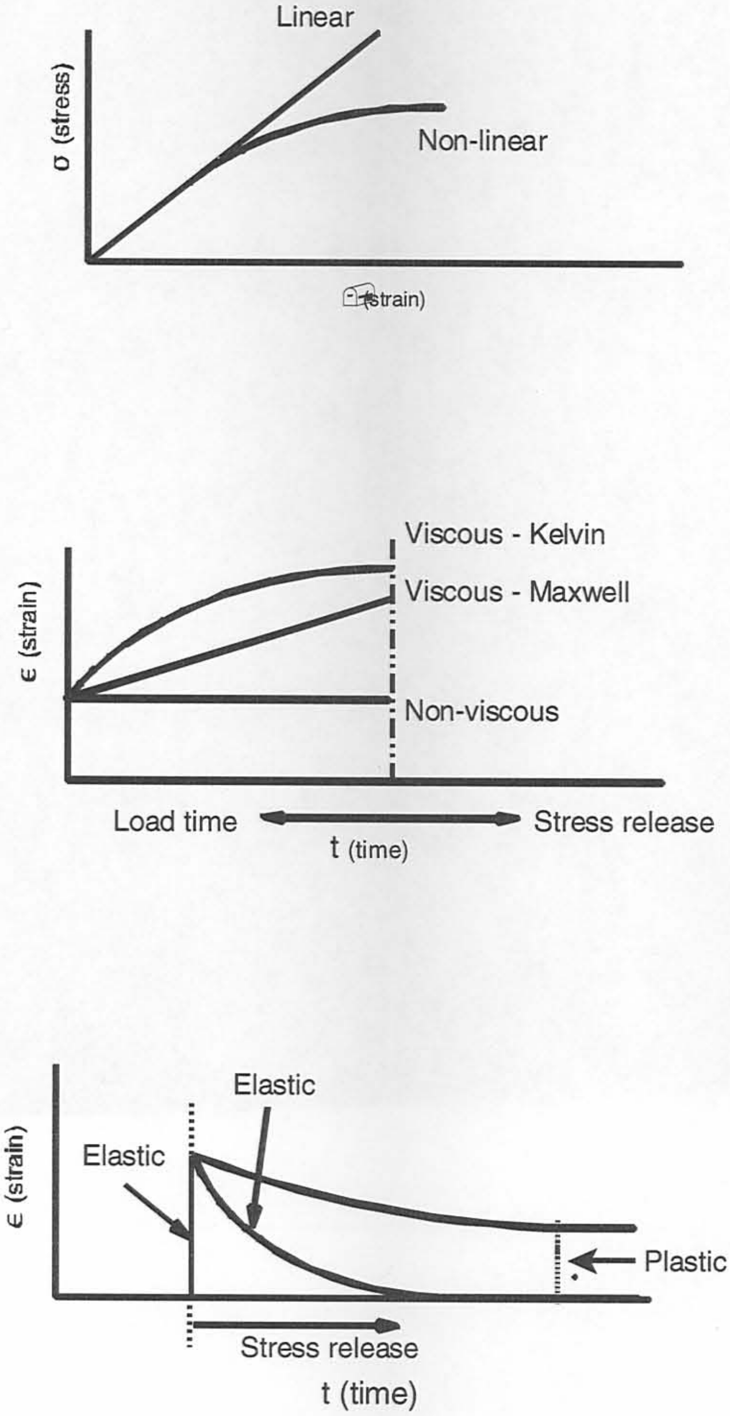


Figure 2.6: **Material characteristics (after Yoder and Witczak, 1974).**

$$E^{*} = \frac{\sigma_0}{\varepsilon_0}\left[\cos\ \delta + i\sin\ \delta\right] = E_1 + iE_2$$

where

E^{*} – complex modulus [MPa]

σ – applied stress [MPa]

ε – strain

δ – phase angle

E_1 – in – phase component of complex modulus [MPa]

E_2 – out – of – phase component of complex modulus [MPa]

Equation 2-5: Complex modulus (Jooste, 1997).

The material parameters used in the Burgers model are the spring stiffnesses and the coulomb damping factors. These parameters can be established using a dynamic or complex modulus experiment where an oscillatory stress is applied to the specimen. The strain response for an oscillatory stress of σ_0 sinωt will be ε_0 sin(ωt + δ). δ is the phase angle by which the strain response lags the stress response. The complex modulus (E*) can be calculated using Equation 2-5 and the mechanical loss using Equation 2-6. Equation 2-7 provides means for calculating the spring stiffnesses and coulomb damping factors for use in the Burgers model.

$$\tan\ \delta = \frac{E_2}{E_1}$$

Equation 2-6: Mechanical loss (Jooste, 1997).

$$E^{*} = \frac{\left(\left[p\ q_1\omega^2 - q_2\omega^2\left(1 - p_2\omega^2\right)\right] + i\left[p_1 q_2\omega^2 + q_1\left(1 - p_2\omega^2\right)\right]\right)}{\left(p_1^2\omega^2 + \left(1 - p_2\omega^2\right)^2\right)}$$

where

$$p_1 = \frac{\eta_1}{E_1} + \frac{\eta_1}{E_2} + \frac{\eta_2}{E_2}$$

$$p_2 = \frac{\left(\eta_1\eta_2\right)}{\left(E_1E_2\right)}$$

$$q_1 = \eta_1$$

$$q_2 = \frac{\left(\eta_1\eta_2\right)}{E_2}$$

E, η from Equation 2 – 4

Equation 2-7: Spring stiffness and coulomb damping factors for Burgers model (Jooste, 1997).

Granular materials typically behave in a non-linear elastic mode (Sweere, 1990). Sweere (1990) identified a modified Boyce's G-K model for predicting the resilient stress-strain behaviour of granular materials, where the stresses and strains are separated into volumetric and shear components. The model is shown in Equations 2.8 and 2.9. Motrescu and Visser (1995) identified non-linear elastic models for describing the permanent deformation behaviour of granular materials. They identified the approach followed by Brown and Pappin to provide an adequate model of granular material plastic deformation (Equation 2.10). This is the only model allowing the influence of residual stresses to be modelled. It was shown to produce results that were in good agreement with all aspects of granular material behaviour, provided that a residual stress component (7 to 14 kPa) induced by compaction is postulated.

$$\varepsilon_v = \frac{1}{K_1 \, p^n \left(1 - \beta q^2 / p^2\right)}$$

Equation 2-8: Volumetric strain (Sweere, 1990).

$$\varepsilon_s = \frac{1}{3 \, G_1 \, p^m \, q/p}$$

where

K_1 – bulk modulus [MPa]

G_1 – shear modulus [MPa]

n, m – stress – dependency factors (1 – linear elastic, 0 – minimum)

β – damping coefficient

$$p - \frac{1}{3(\sigma_1 + \sigma_2 + \sigma_3)} \text{ [MPa]}$$

$$q - \frac{1}{\sqrt{2\left\{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right\}^{0.5}}} \text{ [MPa]}$$

Equation 2-9: Shear strain (Sweere, 1990).

$$M_r = k_1 \, \theta^{k_2} \, \sigma_d \, k_3$$

where

M_r – resilient modulus [MPa]

k1, k2, k3 – material constants

θ – sum of principal stresses [MPa]

σ_d – deviatoric stress [MPa]

Equation 2-10: Resilient modulus (Motrescu and Visser, 1995).

The material parameters needed for evaluation of the granular material constitutive equations have traditionally been measured using tri-axial tests. The five material parameters for Equations 2-8 and 2-9 can be determined using a regression analysis from resiliency tests, while the principal stresses can be calculated from the input and output data of the tri-axial tests.

$$E_R = k_1 \, \theta^{k_2}$$

where

E_R – resilient modulus [MPa]

k_1, k_2 – material parameters

θ – sum of the principle stresses [MPa]

Equation 2-11: Typical k-Θ model (Uzan, 1985).

Lightly cemented materials typically behave in a linear elastic mode, especially when used as subbase layers and during the initial phase of their lives. Slight non-linear (stress-stiffening) behaviour may develop towards the effective granular phase (De Beer, 1998). For the purposes of this thesis a typical k-θ model (Equation 2-11) is used for describing resilient behaviour (Uzan, 1985). Tri-axial test can again be used to determine the various material parameters needed. The material parameters for the two phases have to be evaluated separately.

Subgrade soils normally behave in a non-linear elastic mode (Brown, 1996). Motrescu and Visser (1995) identified several non-linear elastic models. They indicated that both the Second stress invariant model and the Cornell constitutive model can be used for subgrade material modelling. As typical values for the material constants could not be obtained from the literature, the Brown and Pappin model (Equation 2-10) is again used in this thesis. The parameters needed for evaluation of Equation 2-10 for subgrade materials are shown in Table 2.3 with typical ranges.

A summary of the material properties needed to evaluate the various equations, together with the typical method for evaluation and published values of these parameters are shown in Table 2.3. Current methods for evaluating these parameters cost-effectively are evaluated and discussed in Chapter 6 of this thesis.

The constitutive equations selected for the various materials indicate that only the asphalt is sensitive to load frequency (time-dependent behaviour). All of the other materials are stress level dependent.

Mamlouk (1987) emphasised that the accuracy of any transient pavement analysis technique ultimately depends on the accuracy by which the materials are characterised. Desai and Gallagher (1984) further indicated that dynamic analysis is intimately related to the capability of measuring the necessary soil properties. These two vital aspects are further addressed in later chapters of this thesis.

Table 2.3: Material properties needed for each material type in analysis.

Material	Model (Equation)	Parameter	Method	Typical published values
Asphalt (AC)	Burgers (Equation 2.5)	σ [kPa]	Dynamic modulus	690 kPa[a]
		$\eta_{1,2}$ [MPa.s]		5000, 1000[a]
		$E_{1,2}$ [MPa]		2000, 1500[a]
Granular (G1, G2, G6)	Modified G-K (Equations 2.8 and 2.9)	k_1 [MPa]	Tri-axial test	57 MPa
		G_1 [MPa]		404 MPa
		β		0.17[b]
		n		1.00[b]
		m		0.33[b]
	Brown-Pappin (Equation 2.10)	σ_3 [kPa]	Tri-axial test	0,1 to 4,4[c]
		σ_d [kPa]		0,7 to 9,3[c]
		k_1		128 to 1282[c]
		k_2		0,32 to 1,49[c]
		k_3		-0,08 to -1,53[c]
Cemented (C3, C4)	Uzan (Equation 2.11)	$\Sigma_1, \sigma_2, \sigma_3$	Tri-axial test	200, 50, 50[d]
		k_1		E = 200 to 600[d]
		k_2		0[d]
Subgrade (SG1)	Brown-Pappin (Equation 2.10)	σ_3 [kPa]	Tri-axial test	0,0 to 0,9
		σ_d [kPa]		0,3 to 1,5
		k_1		46 to 340[c]
		k_2		0,09 to 0,51[c]
		k_3		-0,32 to -1,38[c]

a. Jooste (1997). Typical thick (120 mm) asphalt on crushed stone base and gravel subbase.
b. Sweere (1990). Crushed concrete.
c. Rohde (1990). Various granular base courses and sandy subgrade materials.
d. De Beer (1998). Various base and subbase applications of lightly cemented materials.

2.5.3 Transient Response Analysis of Pavement Structures

In this thesis pavement response analysis techniques are used as toolboxes for obtaining the transient response of pavements under varying conditions. The mathematical background of these techniques is only covered as background information. The limitations of the identified techniques are thus not specifically investigated, although such limitations that may influence the outcome of analyses are discussed.

The process of mechanistic pavement analysis effectively consists of four steps:

a. Definition of the pavement problem in mathematical terms (conversion from physical reality to mathematical model);
b. Calculation of the stresses and strains in the pavement structure using an analysis technique and material constitutive laws (conversion of stresses to strains and displacements in pavement);
c. Calculation of the expected lives of the various components using transfer functions (conversion of stresses, strains and displacements to damage parameters), and
d. Calculation of the economic life of the pavement (conversion of damage parameters to economic terms) (Haas et al, 1994).

The focus of this thesis is on steps a and b of this process.

Three different approaches can be followed in pavement analysis. These are the static, quasi-transient and transient approaches (Chatti, 1992). The static approach has been used traditionally (and continues to be used). Either elastic layer theory or finite element approaches are used for analysing flexible pavements. No inertia or damping effects are quantified in the pavement.

The quasi-transient approach is based on the concept of positioning the load at subsequent positions along the pavement for each new time step, and assuming the load to be static at each position. Using static analysis the loading position causing the most severe effect is determined via influence lines which provide the variation in the static response at a fixed point due to a unit load traversing the pavement. The quasi-static approach has been justified by the fact that traffic velocities are less than 10 per cent of the critical velocity (propagation velocity of a transverse displacement wave through the pavement) of typical pavements. Sousa et al (1988) indicated that inclusion of dynamic effects might be validated if the stress field caused by a group of tyres are considered, but that a quasi-transient approach should be valid under certain combinations of load types, vehicle velocities, pavement stiffness and pavement roughness.

The transient approach is based on analysis of a layered structure of solids. Transient models vary in complexity depending on the structure and load characteristics. Zafir et al (1994) stated that there are two important factors that should be considered in any transient pavement analysis. These are the inertia associated with the moving load and the dependency of the material properties on the applied stress and the loading frequency. The fluctuation nature of the applied load should also be considered if actual conditions are simulated. The loading frequency effect is considered through the use of appropriate material constitutive equations.

Two basic approaches for incorporating transient pavement structure response to tyre loading were identified in the literature. Either of these two approaches can be used to develop the differential equations needed for solution of the problem. Each approach has some unique features and limitations, which are discussed briefly in this section.

The first approach is that using Newton's second law of motion (Lourens, 1992; Cook, 1995; Jooste and Lourens, 1998). The transient response of the pavement structure is described using an Ordinary Differential Equation (ODE) with parameters characterising the stiffness, damping and mass of the pavement materials (Equation 2-12). These parameters are used to solve for the displacements in the pavement structure due to a specified load function. The displacements are used together with the constitutive equations for the various pavement materials to calculate the stresses and strains in the pavement structure.

$$F(t) = K\,u(t) + C\,u'(t) + M\,u''(t)$$

where

$F(t)$ – loading function

K – stiffness matrix

C – damping matrix

M – mass matrix

$u(t)$ – displacement matrix

$u'(t)$ – velocity matrix

$u''(t)$ – acceleration matrix

Equation 2-12: Ordinary Differential Equation for transient response of pavement structure.

The essential material parameters are the stiffnesses, mass properties and damping coefficients of the layer materials. Some authors (Lourens, 1992) use the Young's modulus for quantification of the stiffness matrix. It may be argued that the resilient modulus (Monismith, 1992) or effective elastic modulus (De Beer et al, 1997b) may also be appropriate parameters. The resilient modulus refers to the relationship between the applied stress and recoverable strain measured in a repeated load test (Monismith, 1992). The effective elastic modulus refers to the elastic modulus obtained from backcalculation of in situ Multidepth Deflectometer (MDD) measured elastic deflections (De Beer et al, 1997b).

The mass properties typically depend on the unit mass density of the material in the layer. The damping coefficients can be determined using typically tests such as the resonant column (Jordaan, 1996; Allen and Deen, 1980). Jordaan (1996) indicated that the test is expensive and fairly sophisticated, and has seldom been used in South Africa. Hardin and Drnevich (1972) have also shown that load-deflection tests yielding a shear-stress shear-strain curve can be used to calculate the damping coefficient from the area of the load-unload hysteresis curve. Typical values for the stiffness, mass and damping parameters for typical South African pavement materials are shown in Table 2.4.

The second approach (Mamlouk, 1987; Sebaaly et al, 1985; Davies and Mamlouk, 1985; Roesset and Stokoe, 1990) is based on the governing equations for elastodynamics (wave equations). These equations are used to develop the Helmholtz Partial Differential Equation (PDE) (the governing equation for steady-state (harmonic) elastodynamics) (Equation 2-13).

Table 2.4: Typical material properties for use in Equation 2.10 (Lourens, 1992).

Material type	Young's modulus [MPa]	Poisson's ratio	Mass [kg/m^3]	Damping ratio D [%]
Asphalt	1 500	0,4	2 400	5
Crushed stone	350	0,35	2 300	5
Stabilised subbase	2 000	0,2	2 000	5
Selected layer	200	0,4	2 000	5
Natural soil	100	0,4	2 000	5

$$G\Delta\Delta + (\lambda + G)\nabla\nabla \bullet u = -\rho\omega^2 u$$

where

λ, G – Lame's constants

ρ – mass density

ω – circular frequency of excitation

u_i – i^{th} cartesian component of displacement vector

Δ – Laplacian operator

∇ – gradient

Equation 2-13: Helmholtz partial differential equation (Mamlouk, 1987; Sebaaly et al, 1985; Davies and Mamlouk, 1985; Roesset and Stokoe, 1990).

Five material parameters are used. These are Young's modulus, Poisson ratio, material damping, mass density and layer thickness (Sebaaly et al, 1985). Material linearity and isotropy and no-slip between layers are assumed. Inertia of a pavement is an explicit part of the elastodynamic analysis and thus no further allowance is necessary. Material damping is accommodated by using the complex modulus (E^*) (Equation 2-14). The various material parameters can again be evaluated using the tri-axial test.

$$E^* = E(1 + 2i\beta)$$

where

E^* – complex modulus [MPa]

E – Young's modulus [MPa]

β – damping ratio [%]

Equation 2-14: Complex modulus (Sebaaly et al, 1985).

The differential equations developed using the two approaches discussed, can be solved using typically one of two approaches. These are either an analytical technique or a numerical technique (Haas et al, 1994).

Various numerical techniques (i.e. finite elements, finite differences, boundary elements) can be applied to the analysis of pavement structures. The numerical technique used in this thesis for the analysis of transient pavement response is the finite element method. The use of finite element methods provide a good estimate of stresses and strains in pavement structures, but slight differences may occur in calculated deflections due to differences in boundary conditions. Finite element methods for the analysis of pavements permit modelling of more complex material characteristics and pavement geometries than is possible with the analytical solution methods (Haas et al, 1994).

The ordinary differential equation (ODE) developed using Newton's second law of motion is used (Equation 2-12). The required forces to balance the pavement's response to input displacements are calculated, followed by calculation of the governing stresses in the pavement body. The strains and deflections throughout the pavement body are calculated using material models (constitutive laws). This procedure is iterative in nature for non-linear and stress-dependant materials. The complexity of the numerical approach used varies. It ranges from simple axi-symmetrical models to full three-dimensional pavement structures. The more advanced models require more computational abilities but also provide more accurate outputs. The assumptions used in the finite element analysis vary depending on the specific technique used. These may include simplifications such as axi-symmetrical load conditions, uniform load distributions and linear elastic material responses.

Hardy and Cebon (1992a; 1992b; 1993; 1994) described the convolution theory (Equation 2-15; general form) as a technique for the analysis of transient pavement response. A solution of the response of the pavement structure to a unit impulse load, as well as the load function, is needed. The integral over the product of these two functions provide the transient response of the pavement structure at a specific time and position. Assumptions with regard to the stiffness of the materials involved have to be made. The assumptions inherent to the specific solution of the response of the pavement structure to a unit impulse load, are transferred to the solution. Hardy and Cebon (1992a; 1992b; 1993; 1994) indicated that the only way to include speed and frequency effects rigorously in road-response calculations is to use a transient road-response model. Their model describes the response of an isotropic dynamically linear pavement to fluctuating loads moving over its surface (Equation 2-16; time domain). They simplified the convolution theory to yield a quasi-transient calculation because they have shown that the effects of loading frequency on pavement strains are relatively minor compared with the effect of speed (for the pavement and loads analysed). In this influence function approach, the effect of load frequency is neglected, while the correct allowance is maintained for vehicle speed and dynamic tyre load magnitudes.

$$y(t) = \int_{-\infty}^{\infty} h(t - \tau)\, f(\tau(\, d\tau$$

where

$y(t)$ – response at time t

$f(\tau($ – input force at time τ

$h(t)$ – response at time t to a unit impulse at time t = 0

Equation 2-15: Convolution theory in general form (Hardy and Cebon (1992a; 1992b; 1993; 1994)).

$$y(x,\ t) = \sum_{m=1}^{N_f} \int_{-\infty}^{t} h\left[x - \left(d_m + v\tau\right),\ t - \tau\right] f_m\left(\tau\right) d\tau$$

where

$y(x, t)$ – response at position x in the wheelpath at time t [m]

N_f – number of inputs (or tyres)

t – time [s]

x – position [m]

d_m – longitudinal position of tyre (force) m at time zero [m]

v – vehicle speed [m/s]

τ – time [s]

f_m – force [kN]

$h(x, t)$ – response at position x and time t to a unit impulse at the origin at time zero [m]

Equation 2-16: Convolution theory in time domain (Hardy and Cebon (1992a; 1992b; 1993; 1994)).

A typical response function (h(t)) used by Hardy and Cebon (1993) is that for an Euler beam supported by a damped elastic foundation with mass, elastic and damping parameters chosen to simulate the response measured during the AASHO road tests. The response of this type of system to moving harmonic loads, where the loads are simulated by a linear quarter-car model running over a 10 mm step to excite the vehicle was evaluated and found to agree with expected results.

Markow et al (1988) described a quasi-transient method for incorporating dynamic load effects on pavement response calculations. They argued that the pavement response to a load P at a distance x is assumed to be equivalent to the response to a lesser load P' placed directly at the position of interest. The response at a specific position (x_0) due to an arbitrary load F(x) is therefore the product of the influence function (I) and the force function (Equation 2-17). This technique appears very similar to the convolution approach.

$$R(x_0) = I(x_0 - x)F(x)$$

Equation 2-17: Response of pavement due to force F using quasi-transient method (Markow, 1988).

It forms part of this thesis to evaluate the different techniques described for their appropriateness in analysing pavement structures dynamically. Although the focus is more on materials and pavement parameters, the use of different mathematical tools and/or the development of new ones where necessary and appropriate are not excluded from this thesis.

2.5.4 Parameter effects

Some of the more well-researched and proven effects of the various vehicle, pavement and material parameters are presented in this section. The focus is specifically on those issues where a static and dynamic load application and pavement response will differ. The objective is to highlight possible interaction issues and identify the parameters of importance. Only the results of such research are highlighted, and detail information with regard to the test conditions and background can be found in the references indicated. Some of the findings may be more focussed on the behaviour of the thicker asphaltic layers.

Very little work has been done on the response of typical South African pavement structures with thinner surfacing layers and thicker granular and cemented layers to dynamic loads and transient response. De Beer (1991) did some work on the elastic deflections caused by heavy vehicles when running at speed, and Lourens (1992) performed some measurements and analysis on transient pavement response to dynamic load conditions. Recently, Jooste and Lourens (1998) investigated the effect of dynamic analysis versus static analysis on asphalt pavements.

Lourens (1992) and Chatti et al (1995) found that the vertical stresses in the asphalt decrease with increased load speed. The influence sphere of the load moved shallower, and the total surface deflection increased. The Radius of Curvature (RoC) also increased. The speed effect is more pronounced on surface deflection than on tensile strain in the asphalt layer. The increased dynamic load levels, strains and fatigue may be offset by the shorter load duration. On rougher pavements the additional strains may dominate (increasing fatigue levels) while on smoother pavements the load duration may dominate, leading to decreased fatigue. This is very dependent on the models and actual response of the pavement materials (Gillespie et al, 1993). Hardy and Cebon (1994) found that material frequency dependence might be part of the cause for different pavement reactions at different speeds.

Gillespie et al (1993) found a linear relationship between pavement rut and gross vehicle load magnitude and duration. The layer thicknesses were the only parameter comparable in magnitude of influence on damage to axle load. Increases in load speed caused increased load magnitudes but decreased load durations (increased load frequency). Suspension type did not influence rut development. Single tyres were shown to cause increased rut depths but similar rut volumes (in terms of volume of material displaced) than for dual tyres operating at the same load. Tyre inflation pressure affects the contact area and load duration. Increased tyre inflation pressures cause higher strains but at shorter load durations in the pavement (Chatti et al, 1995). Radial tyres tend to concentrate on the wheelpaths, causing potentially increased rut.

Single axle suspension type has a limited effect on fatigue levels. Tandem axle dynamics, however show a definite influence of suspension type with between 25 and 50 per cent differences in dynamic loads developed due to suspension types. Increased pavement roughness levels may increase fatigue between 50 and 400 per cent (Gillespie et al, 1993).

Kenis et al (1997) found the mean dynamic load independent of the speed, and close to the static load.

De Beer (1991) showed the existence of a phase lag between the point of maximum load and the point of maximum strain. This phase lag was dependent on the load speed. Mamlouk (1987) indicated that this load-deflection time lag is mainly due to inertia effects in the pavement.

The range of compressive to tensile strain of the strain cycle is important when evaluating the fatigue behaviour of the materials in the pavement. Fatigue damage is highly influenced by surfacing thickness with thinner surfacings being affected more than thicker surfacings (Gillespie et al, 1993).

Jooste and Lourens (1998) indicated that static response models could overestimate tensile strains in the asphalt by more than 50 per cent. For the pavements investigated, the effect of transient pavement analysis was more important than the effect of non-uniform tyre inflation pressures, random variations in asphalt stiffness and layer thickness, and visco-elastic effects. Lourens (1992) showed that the stresses and deflections in the pavement structure differ substantially for static and dynamic loads. The existence of a remnant stress in the pavement after the passing of the load was indicated. The magnitude of this stress is dependent on the load speed.

Hardin and Drnevich (1972) found the strain amplitude, effective mean principal stress and void ratio to be of prime importance in the value of the shear modulus (G) and the damping coefficient of the material. They showed that increased strain amplitude cause decreased shear modulus and increased damping ratios. Increasing effective mean principal stress cause increasing shear modulus and damping coefficient, and increasing void ratios cause decreasing shear moduli and damping coefficient. Vuceti et al (1998) indicated that the shape of the cyclic loading cycle affects the measured damping coefficient and should be clearly defined when reporting results.

Heukelom and Klomp (1967) indicated that increased temperatures might cause asphalt stiffness to decrease. De Beer et al (1997b) indicated that increased moisture condition might cause a decrease in unbound granular stiffness. Decreased load durations may cause increases in asphalt stiffness. Stress level mainly influence unbound granular stiffness. Very low densities may cause decreases in stiffness for most materials.

2.5.5 Conclusions

The objective of this section was to provide the current state of information regarding pavement components and their importance in dynamic vehicle-pavement interaction, to enable further development and application work to be performed.

Constitutive equations were identified for the four main material types identified as appearing in typical South African pavements.

Two methods for developing the differential equations for analysis of transient response of pavement structures to dynamic loads were identified. Two different solving methods for the problems were discussed.

Current literature indicates that primary pavement response (stresses, strains and deflections) is strongly influenced by vehicle speed. Material parameters are also influenced by factors such as load duration, stress levels and environmental conditions. A thorough definition of operating conditions thus needs to be defined for any analysis of transient pavement response.

2.6 South African Vehicle and Pavement Fingerprinting

2.6.1 Introduction

This section focuses on identification of typical vehicle and pavement components currently used in South Africa (fingerprinting). These data are needed as input to the analyses in Chapters 5 and 6. The correct input data are vital as the cause for many differences in pavement engineering and the management thereof between South Africa and the USA and Europe, is the different pavement materials, structures and vehicle populations. If relevant and valid conclusions and guidelines for South African conditions are to be developed it is vital to ensure use of typical local information.

The data in this section originate from various sources. The type of data needed is not currently freely available in South Africa. Typical sources are the National Traffic Information System (NATIS), the South African National Roads Agency Ltd (SANRAL), provincial pavement management system (PMS) databases, tyre, suspension and vehicle manufacturers, fleet operators and various other publications citing statistics regarding vehicles and roads.

Some difficulties in collecting this type of information should be appreciated. The component manufacturers and fleet operators are generally not willing to part with information they regard as strategic to their business. Trends and assumptions thus have to be used as input for these parameters. It is expensive in terms of money, manpower and time 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.

Pavement structure information is scattered and not always in a user-friendly format. Due to the change from four to nine provinces in 1994, the databases are not all up to date and due to funding problems, it is doubted whether these databases will be running effectively in the near future. Some of the road agencies and departments do still provide a valid service in this regard, and the focus of this fingerprinting effort was on their information. Some bias may thus exist in the information.

The information provided should be viewed as the best available under conditions of secrecy and logistical problems. It is one of the recommendations of this thesis that a thorough fingerprinting of South African heavy vehicles, components and pavements be performed on a regular basis to enable pavement engineers and managers to operate more effectively.

2.6.2 Vehicles and components

The vehicle components of importance in this thesis are the tyres, suspension, load and vehicle configuration and dimensions.

Radial tyres are currently increasing in popularity in South Africa, with estimates ranging between 50 and 70 per cent of the heavy vehicle market (Barnard, 1997; Campbell, 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 (between 50 and 59 per cent) followed by the 315/80R22.5 (between 19 and 27 per cent) (SATMC, 1997; Steyn and Fisher, 1997). Although previous studies (Van Niekerk, 1992) identified the use of super single tyres as a possible increasing trend in South Africa, recent information indicates their use to be limited to 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). Data indicate that typical tyre inflation pressures on steering axles for cross-border vehicles is 729 kPa (Standard Deviation of 125 kPa) while the average tyre inflation pressure on non-steer axles are 670 kPa (Standard Deviation of 87 kPa) (Steyn and Fisher, 1997).

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).

The important suspension parameters for evaluating dynamic performance of vehicles include the composite vertical stiffness, composite roll stiffness and damping (Pretorius, 1990). Typical values were obtained from Pretorius (1990) and are shown in the summary in Table 2.5.

The system used for vehicle classification is based on the number of axles of a heavy vehicle. Previous studies (Pretorius, 1990) have used a combination of the number of axles and drive axles on truck-tractors and rigid vehicles, and a combination of truck-tractor axles and trailer axles to classify truck-tractors and trailers with separately. However, as these vehicles are mostly used in combination the author decided to make use of the system where the total number of axles in each of the axle groups on a vehicle or combination are used to classify the vehicle or combination (Nordengen et al, 1995). The thirteen most typical vehicles and/or combinations identified for South African conditions are shown in Table 2.6, together with their respective unladen masses, number of axles, number of axle groups and population as determined for internal use and cross border use.

An attempt was made to establish the percentage of each of the various classes of vehicles on South African roads. The current National Traffic Information System (NATIS) is not up to date and therefore data from the National Association of Automobile Manufacturers in South Africa (NAAMSA) were used to establish the internal heavy vehicle spectrum (NAAMSA, 1998). Data from the annual cross-border surveys undertaken by the CSIR were used to indicate the vehicle population crossing South African borders (Nordengen et al, 1995). As these data are compiled for slightly different parameters than the classification used, the thirteen classes have been simplified to 6 classes for the internal traffic and 3 classes for the cross border traffic.

For the purposes of pavement response the number of axles, distance between individual axles, distance between axle groups and individual axle loads of vehicles and vehicle combinations are important. The data used in this thesis are based on a survey conducted at the Beitbridge borderpost (Steyn and Fisher, 1997). The data compare favourably with published data on specific vehicles. These data are shown in Table 2.6 for three of the most typical combinations used in South Africa. These are the 11, 123 and 1222 classes. These three classes are used for the further analyses in this thesis, as they constitute (according to the available data) three of the most popular vehicle classes, and they further represent a rigid vehicle, a combination of a truck tractor and one semi-trailer (2 separate bodies) and a combination of a truck tractor and two semi-trailers (3 separate bodies).

The maximum allowable legal axle loads and dimensions of heavy vehicles in South Africa, are regulated in the national road traffic act (Wessels, 1996). These data for the three typical vehicle types identified for further use in this thesis are shown in Table 2.5.

Average speeds for heavy vehicles (GVM > 7 000 kg, average number of axles 4.2) on national roads in South Africa were 79.9 km/h (standard deviation 10.2 km/h) (Bosman et al, 1995). This is similar to the legal speed limit of 80 km/h for trucks on the 40 roads included in the calculation.

The vehicle response software (Section 2.4.3) requires the Pitch Moments of Inertia (MoI) of the truck, trailer and payload as input. Typical calculated values are shown in Table 2.6.

2.6.3 Pavements and components

The physical pavement components for which information is required are material type and properties, layer thickness, layer combinations and pavement roughness. Selected typical trends and statistics for South African pavements and pavement structures are given in this section. The data should be seen as the most probable breakdown of surfacing and base layer type for South African conditions given the limitations indicated in Section 2.6.1. It is based on information from the national and six of the provincial road authorities.

Table 2.5: Matrix of vehicle components to be used in this thesis.

Parameter	Unit[1]	11		122			1222			
Tyre type		12R22.5 Radial								
Tyre inflation pressure	kPa	730	670	730	670		730	670		
Tyre spring rate	lb/in/tyre	4 800	4 800	4 800	4 800	4 800	4 800	4 800	4 800	4 800
Suspension type		Steel								
Spring rate	lb/in/side	1 000	1 500	800	5 000	6 000	800	5 000	6 000	6 000
Viscous damping rate	in/second/ side	15	0	15	0	0	15	0	0	0
Coulomb damping rate		500	1 000	500	1 000	1 000	500	1 000	1 000	1 000
Unsprung weight	lb/axle	1 200	2 300	1 200	2 300	1 760	1 200	2 300	1 760	1 760
Pitch MOI[2] truck	1 000 in.lb.sec^2	102		147						
Pitch MOI Trailer						661				
Pitch MOI payload		390		2 310						
Permissible Vehicle combination mass	tonne	16,5		43,5			56,0			
Unladen vehicle combination mass		6,5		15,0			20,0			
Achievable payload		10,0		28,5			36,0			
Axle load		7,7	9,0	7,7	18,0	18,0	7,7	18,0	18,0	18,0
Length	m						22			
Width		2,5		2,5			2,5			
Distance between axles on tandem		1,4 (0,03)								
Distance between first and second axle groups		4,8 (0,47)		3,1 (0,56)			3,1 (0,56)			
Distance between second and third axle groups						6,3 (1,1)			6,3 (1,1)	
Distance between third and fourth axle groups										6,4 (1,5)

All distances are between the centreline of the last tyre of the first axle group and the centreline of the first tyre of the following axle group.

Values in brackets indicate standard deviation.

---

[1] A combination of imperial and metric units are shown as sourced from the various references.

[2] Moment of Inertia

Table 2.6: Heavy vehicle classes and population in South Africa (based on NAAMSA, 1998; Nordengen et al, 1995).

Class	Type*	Unladen vehicle / combination mass [tonne]	Number of axles	Number of axle groups	Internal use [%] (NAAMSA, 1998)	Cross border use [%] (Nordengen et al,1995)
11	R	< 7,5	2	2	37,9	23,2
12	R	7,5-10,0	3	2	5,5	
111	TT+ST		3	3		
112	TT+ST	10,0-12,5	4	3	11,0	17,5
22	R+T		4	2		
1111	R+T		4	4		
122	TT+ST	12,5-15,0	5	3	20,9	
113	TT+ST		5	3		
123	TT+ST	15,0-17,5	6	3	4,1	59,3
1222	IL	> 17,5	7	4	20,6	
1222	TT+T		7	4		
1232	IL		8	4		
1222	IL+T		7	4		

* Indicates the individual vehicle of which the combination consists. R - Rigid, TT - Truck Tractor, ST - Semi-Trailer, IL - Interlink, T - Trailer

These data indicate that approximately 39 per cent of the provincial roads that appear on the pavement management databases are paved. However, if unpaved roads currently not appearing on the provincial databases are included, this figure should decrease to approximately 16 per cent provincial paved roads for the whole country (Steyn, 1997). All the national roads are paved. The percentage breakdown of current surfacing types and base layer material types are given in Table 2.7.

Typical pavement structures are proposed in the catalogue of TRH4 (1996). For the purposes of this thesis three typical pavement structures were selected for analysis. The first structure (resembling typical national roads) consists of an asphalt surfacing with a G1/G2 base layer, the second (resembling a typical provincial road) consists of a seal and a cemented base layer and the third (resembling a typical rural road) consists of a seal and a granular base layer. The structures are shown in Table 2.8. The traffic class for the national road is ES100 (30 to 100 million 80 kN axles / lane) road category A for dry regions, while that for the provincial roads are ES3 (1 to 3 million 80 kN axles / lane) road category B, and ES0,3 (0,1 to 0,3 million 80 kN axles / lane) road category C. These three structures are seen as representative of typical South African pavements.

Table 2.7: Percentage breakdown of surfacing and base layer material types for South African National and Provincial roads (Steyn, 1997; Kannemeyer, 1997; Provincial PMS data, 1997).

Pavement / layer type		National roads	Provincial roads	All roads
Surfacing type	Seal	46,3	82,5	75,2
	Asphalt	44,6	2,4	11,8
	Slurry	0,0	3,6	1,9
	Other	9,1	11,5	11,1
Base layer material	G1/G2 Crushed stone	56,0	17,8	25,4
	Cemented	13,0	34,7	30,4
	Gravel	9,0	37,8	32,0
	Other	22,0	9,7	12,2

Table 2.8: Typical pavement structures analysed in this thesis (from TRH4).

Layer	National road structure	Provincial road structure	Rural road structure
Surfacing	50 mm Asphalt	Double seal	Double seal
Base	150 mm G1	125 mm C3	125 mm G4
Subbase	300 mm C3	152 mm C4	125 mm G6
Subgrade	500 mm SG1	500 mm SG1	500 mm SG1

The typical flexible materials found in South Africa are shown in TRH14 (1985). These materials can be classified into natural unbound, natural bound, lightly stabilised, strongly stabilised and asphaltic materials. Each of these types of materials has various subclasses, depending on the origin of the material, the way in which it was treated, the physical properties of the material and the way in which it is normally used.

The focus in this thesis is on the eight types of materials used in the three typical pavement structures shown in Table 2.8. Double seals are typically not assumed to contribute to the structural capacity of pavements, and no constitutive equations exist for them. For the remaining seven materials, constitutive equations and typical material parameters are discussed in Section 2.5.3.

The typical road roughnesses for South African national roads have been shown to be mainly (87,4 per cent) less than and equal to 2,5 IRI. The average is 2,0 IRI with a standard deviation of 0,6 IRI (Kannemeyer, 1998). Based on these values three typical pavements with roughnesses of 1,4, 2,0 and 2,6 are selected for analysis.

2.6.4 Summary

Based on the information collected and provided in this section, the matrix of information provided in Tables 2.6 and 2.8 summarises the input data for the analyses to be performed in this thesis. These matrices are based on the parameters that occur most frequently in the various components. From the phenomenological approach taken in this study, it is believed that focus on these major parameters should provide a deeper understanding of the governing principles in dynamic load and pavement response.

2.7 Conclusions

The objective of this chapter is to provide relevant background information needed for further studies in the subjects addressed in this thesis. In this regard, the following conclusions are drawn for the five main themes addressed:

Vehicle-pavement interaction systems.
Various systems are available for describing vehicle-pavement interaction. The dominant features and limitations of the systems were shown. Major limitations that need attention are the bias towards either vehicles or pavements, the uncertainty regarding the use of behavioural models or performance models, and the level of complexity at which the system should be analysed. A robust system should be developed allowing all the major factors to be evaluated on an equal footing.

Pavement roughness.
Pavement roughness is the main cause for dynamic loads. The IRI and TRRI were selected as indicators of roughness levels for this thesis. Actual HSP data will be used as indicators of pavement roughness in this thesis.

Vehicle components.
The main vehicle components identified as important in vehicle-pavement interaction are the tyres, suspension, vehicle dimensions, configuration and load. DADS and TFP will be used as vehicle simulation models for this thesis. Dynamic load appears to consist of two distinct phases that needs consideration in vehicle-pavement interaction.

Pavement components.
Material constitutive models were identified for the main materials evaluated in this thesis. The different methods available for describing transient pavement response were described. Vehicle speed, stress level and environmental conditions were identified as the major factors in influencing transient pavement response. A good understanding of material properties is needed if a transient pavement response analysis is attempted. More work needs to be done on evaluating the available material constitutive models and parameter values. The actual factors of importance and their relative contributions to pavement response for South African conditions should be evaluated. A standard process needs to be developed for transient analysis of pavement response.

Fingerprinting..
Three typical vehicle combinations and three typical pavement structures were identified as typical of South African conditions, and further analysis in this thesis will focus on these. Difficulties were experienced in obtaining valid information on both vehicle and pavement components. A thorough fingerprinting of the important pavement and vehicle issues should be performed on a regular basis to ensure availability of valid data to industry.

2.8 References

ALLEN, D.F. and DEEN, R.C. 1980. **Modulus and damping of asphaltic concrete using the resonant column.** Geotechnical Testing Journal, Volume 3, Number 4, pp 167-171.

ASTM see Terminology related to travelled surface characteristics.

BARNARD, J. 1997. **Personal communication on the tyre industry.** Brits: Firestone South Africa, Technical manager.

BOSMAN, J., VORSTER, A.W. and BOTHA, H.P. 1995. **Comprehensive traffic observations: Yearbook 1993.** Pretoria: Department of Transport. (PR-CTO/1/1995).

BROWN, S.F. 1996. **Soil mechanics in pavement engineering.** In: Geotechnique, Volume 46, Number 3, pp 383-426.

CAMPBELL, J. 1997. **Personal communication on South African heavy vehicle industry.** Randburg: Unitrans Ltd, Technical manager.

CHATTI, K. 1992. **Dynamic analysis of jointed concrete pavements subjected to moving transient loads.** PhD thesis. University of California at Berkeley, Berkeley.

CHATTI, K., MAHONEY, J.P., MONISMITH, C.L. and MORAM, T. 1995. **Field response and dynamic modelling of an asphalt concrete pavement section under moving heavy trucks.** In: Road Transport Technology - 4, Proceedings of the Fourth International Symposium on Heavy Vehicles and Dimensions; edited by C.B. Winkler, Ann Arbor: University of Michigan Transportation Research Institute, pp 189-200.

COLLOP, A.C. and CEBON, D. 1995a. **Parametric study of factors affecting flexible-pavement performance.** Journal of Transportation Engineering, Volume 121, Number 6, pp 485-494.

COLLOP, A. and CEBON, D. 1995b. **Modelling whole-life pavement performance.** In: Road Transport Technology 4; edited by C.B. Winkler. (Proceedings of the fourth international symposium on heavy vehicles and dimensions, held in Ann Arbor, MI, 25-29 June 1995). Ann Arbor, MI: University of Michigan Transportation Research Institute.

COOK, R.D. 1995. **Finite element modelling for stress analysis.** Madison, University of Wisconsin: Wiley.

DADS. 1997. **Dynamic analysis and design system.** User's guide. Revision 8.5.

DAVIES, T.G. and MAMLOUK, M.S. 1985. **Theoretical response of multilayer pavement systems to dynamic non-destructive testing.** In: Analysis and testing of granular bases and subbases. Washington, DC: Transportation research Board, National Research Council. (Transportation Research Record; 1022) pp 1-6.

DESAI, C.S. and GALLAGHER, R.H. 1984. **Mechanics of engineering materials.** Tucson, Arizona: Wiley Interscience.

DE BEER, M. 1991. **Pavement response measuring system.** Paper presented at the 2nd International Symposium on Pavement Response Monitoring Systems for Roads and Airfields, September 6-9, Hanover, New Hampshire, USA.

DE BEER, M. 1992. **Developments in the failure criteria of the South African Mechanistic Design procedure for asphalt pavements.** In: Proceedings of the 7th International Conference on Asphalt Pavements, 1992, Nottingham, UK.

DE BEER, M., FISHER, C. and JOOSTE, F.J. 1997a. **Determination of pneumatic tyre/pavement interface contact stresses under moving loads and some effects on pavements with thin asphalt surfacing layers.** In: Proceedings of the 8th International Conference on Asphalt Pavements, August 10-14, 1997, Washington, Seattle, USA.

DE BEER, M., VAN DER MERWE, C.J. and ROHDE, G.T. 1997b. **Rehabilitation design of flexible pavements in South Africa.** Pretoria: Department of Transport. (RR 93/296).

DE BEER, M. 1998. **Personal communication on behaviour of lightly cemented pavement layers.** Pretoria: CSIR, Project leader.

DE PONT, J., THAKUR, K., PIDWERBESKY, B. and STEVEN, B. 1998. **Validating a whole life pavement performance model.** In: Proceedings of the 5th International Symposium on Heavy Vehicles and Dimensions. March 29 to April 2, 1998. Australia.

DIVINE see Dynamic Interaction of Vehicle & Infrastructure Experiment.

Dynamic Interaction of Vehicle & Infrastructure Experiment: Asia-Pacific Concluding Conference. 1997. Melbourne, Australia: ARRB-TR.

FANCHER, P.S. and GILLESPIE, T.D. 1997. **Truck operating characteristics.** Washington, DC: Transportation Research Board, National Research Council. (NCHRP Synthesis of Highway Practice; 241).

GILLESPIE, T.D. 1992. **Fundamentals of vehicle dynamics.** Warrendale, PA: Society for Automotive Engineers.

GILLESPIE, T.D., KARAMIHAS, S.M., SAYERS, M.W. NASIM, M.A., HANSEN, W. and EHSAN, N. 1993. **Effects of heavy-vehicle characteristics on pavement response and performance.** Washington, DC: Transportation Research Board, National Research Council. (National Cooperative Highway research Program Report; 353).

Guidelines for road construction materials. 1985. Pretoria: Committee of Land Transport Officials (COLTO), Department of Transport. (Technical Recommendations for Highways; TRH14).

HAAS, R., HUDSON, W.R. and ZANIEWSKI, J. 1994. **Modern pavement management.** Malabar, Florida: Krieger Publishing Company.

HARDIN, B.O. and DRNEVICH, V.P. 1972. **Shear modulus and damping in soils: Measurement and parameter effects.** Journal of the Soil Mechanics and Foundations Division, Proceedings of the American Society of Civil Engineers, June 1972, pp 603-624.

HARDY, M.S.A. and CEBON, D. 1992a. **Flexible pavement response models for assessing dynamic axle loads.** In: Heavy Vehicles and Roads: technology, safety and policy, Proceedings of the third International Symposium on Heavy Vehicles and Dimensions; edited by D Cebon and C.G.B Mitchell, London: Thomas Telford, pp 65-71.

HARDY, M.S.A. and CEBON, D. 1992b. **The effects of dynamic axle loads on the response and life of flexible pavements.** Proceedings of the 7th International Conference on Asphalt Pavements, Nottingham, UK.

HARDY, M.S.A. and CEBON, D. 1993. **Response of continuous pavements to moving dynamic loads.** Journal of Engineering Mechanics, Volume 119, No. 9, pp 1762-1780.

HARDY, M.S.A. and CEBON, D. 1994. **Importance of speed and frequency in flexible pavement response.** Journal of Engineering Mechanics, Volume 120, No. 3, pp 463-482.

HEUKELOM, W. and KLOMP, A.J.G. 1967. **Consideration of calculated strains at various depths in connection with the stability of asphalt pavements.** In: Proceedings of the 2nd International Conference on Asphalt Pavements, August 7-11, 1967, Ann Arbor, Michigan, USA.

HUHTALA, M. 1995. **The effect of wheel loads on pavements.** In: Road Transport Technology - 4, Proceedings of the Fourth International Symposium on Heavy Vehicles and Dimensions; edited by C.B. Winkler, Ann Arbor: University of Michigan Transportation Research Institute, pp 235-241.

JANSEN, S.T.H, VAN OOSTEN, J.J.M, and PACEJKA, H.B. 1996. **Modelling and simulation of tyre behaviour in MADYMO; The magic formula tyre model.** In: MADYMO User Conference; Amsterdam: TNO Crash-safety Research Centre, pp 253-258.

JOOSTE, F.J. 1997. **A viscoelastic response model for predicting strain response in asphalt materials.** Pretoria: Division for Roads and Transport Technology, CSIR. (Technical Report TR-97/034).

JOOSTE, F.J. and LOURENS, J.P. 1998. **Appropriate models for estimating stresses and strains in asphalt layers.** Pretoria: Division for Roads and Transport Technology, CSIR. (Technical Report CR-98/060).

KANNEMEYER, L. 1997. **Introducing the International Roughness Index to South Africa.** In: Proceedings for the South African Transport Conference 1997, Volume 2A (Transport Infrastructure 1).

KANNEMEYER, L. 1998. **Personal communication on National Roads Agency Pavement Management System Database.** Pretoria: South African National Roads Agency Ltd.

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

KENIS, W.J., GEORGE, D. And HAMMOUDA, J. 1997. **Pavement primary response to dynamic loading.** Federal Highway Administration: Virginia. (FHWA-RD-97-073).

KENIS, W.J. and HAMMOUDA, J. 1996. **A sensitivity study of some existing truck dynamic simulation programs.** International Journal of Vehicle Design, Volume 3, Numbers 1-4, pp 275-292.

LEBLANC, P.A. and WOODROOFFE, J.H.F. 1995. **Spatial correlation of dynamic wheel loads.** In: Road Transport Technology - 4, Proceedings of the Fourth International Symposium on Heavy Vehicles and Dimensions; edited by C.B. Winkler, Ann Arbor: University of Michigan Transportation Research Institute, pp 281-290.

LIMPERT, R. 1982. **Vehicle system components.** Design and safety. New York, NY: Wiley.

LOURENS, J.P. 1992. **Nonlinear dynamic analysis and design of road pavements.** Pretoria: Department of Transport. (RR 90/030).

MACADAM, C.C., FANCHER, P.S., HU, G.T. and GILLESPIE, T.D. 1980. **A computerised model for simulating the braking and steering dynamics of trucks, tractor-semi-trailers, doubles, and triples combinations - user's manual.** MI: Highway Safety Research Institute, University of Michigan (UM-HSRI-80-58).

MAMLOUK, M.S. 1987. **Dynamic analysis of multilayered pavement structures - theory, significance and verification.** In: Sixth International Conference on Structural Design of Asphalt Pavements. (Proceedings of the 6th International Conference on Asphalt Pavements, held in Ann Arbor, Michigan, July 13 to July 17, 1987). Ann Arbor, Michigan.

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.

MARKOW, M.J., HEDRICK, J.K., BRADEMEYER, B.D. and ABBOO, E. 1988. **Analysing the interactions between dynamic vehicle loads and highway pavements. In: Pavement evaluation and rehabilitation.** Washington, DC: Transportation Research Board, National Research Council. (Transportation Research Record; 1196) pp 161-169.

McClean, J. and RAMSAY, E. 1996. **Interpretations of road profile-roughness data: Review and research needs.** Melbourne, Australia: Australian Road Research Board. (ARRB Research Report 295).

Motor vehicle tyres and rims - dimensions and loads. 1994. Pretoria: South African Bureau of Standards. (South African Standard; SABS 1550-1 to 7 and 10: 1992. (As amended 1993 and 1994)).

MOTRESCU, M. and VISSER, A.T. 1995. **Towards integrated modelling of plastic deformation in pavement layers: an overview.** Pretoria: Annual Transportation Conference, Volume 4A, Paper 10.

NAAMSA, 1998. **Data obtained from NAAMSA database on all new vehicle sales for 1988 to 1998.** Pretoria: National Association for Automobile Manufacturers in South Africa (NAAMSA).

NELL, S. 1998. **Personal communication on DADS (Dynamic analysis and design system) software.** Johannesburg: Reumech Ermetek, Manager, Engineering.

NORDENGEN, P.A., SALLIE, I. and PRETORIUS, J. 1995. **A survey of heavy vehicles crossing the Namibia -South Africa border - final report.** Pretoria: Division for Roads and Transport Technology, CSIR.

ORR, L.W. 1988. **Truck pavement factors - The truck manufacturer's viewpoint.** In: Vehicle / pavement interaction; where the truck meets the road. (Proceedings of the truck and bus meeting and exposition, 1988, Indianapolis, IN). Warrendale, PA: Society of Automotive Engineers (SAE SP-765; pp 1-4).

PAPAGIANNAKIS, A.T. and GUJARATHI, M.S. 1995. **Roughness model describing heavy vehicle-pavement interaction.** In: Pavement-vehicle interaction and traffic monitoring. Washington, DC: Transportation research Board, National Research Council. (Transportation Research Record; 1501) pp 50-59.

PRESTON, A.T. 1996. **Development of a deterministic tyre-pavement interaction model.** M.Eng thesis, University of Canterbury, Canterbury, New Zealand.

PRETORIUS, F.J. 1990. **The dynamic effects of vehicles on flexible pavements.** M.Eng dissertation, University of Stellenbosch, Stellenbosch.

PROVINCIAL DATABASES, 1997. **Communication with the owners and operators of the provincial pavement management system databases.**

ROESSET, J.M. and STOKOE, K.H. 1990. **Dynamic behaviour of pavement structures.** Stellenbosch: Short course presented at the University of Stellenbosch, Stellenbosch.

ROHDE, G.T. 1990. **The mechanistic analysis of pavement deflections on subgrades varying in stiffness with depth.** PhD Thesis, University of Texas A&M, Austin.

SABS 1550 see Motor vehicle tyres and rims - dimensions and loads.

SATMC see South African Tyre Manufacturers Conference.

South African Tyre Manufacturers Conference, 1997. **Personal communications on tyre usage survey of 1997.** Randburg.

SAYERS, M.W. 1995. **On the calculation of international roughness index from longitudinal road profile.** In: Pavement-vehicle interaction and traffic monitoring. Washington, DC: Transportation Research Board, National Research Council (Transportation Research Record; 1501) pp 1-12.

SAYERS, M.W., GILLESPIE, T.D. and PATERSON, W.D.O. 1986a. **Guidelines for conducting and calibrating road roughness measurements.** Washington, D.C., USA: World Bank. (World Bank Technical Paper Number 46).

SAYERS, M.W., GILLESPIE, T.D. and QUEIROZ, C.A.V. 1986b. **The international road roughness experiment. Establishing correlation and a calibration standard for measurements.** Washington, D.C., USA: World Bank. (World Bank Technical Paper Number 45).

SAYERS, M.W. and KARAMIHAS, S.M. 1996. **Interpretation of road roughness profile data.** McLean, Virginia: Federal Highway Administration. (FHWA-RD-96-##).

SAYERS, M.W. 1991a. **Symbolic computer language for multibody systems.** Journal of Guidance, Control and Dynamics. Volume 14, Number 6. pp 1153-1163.

SAYERS, M.W. 1991b. **Symbolic vector/dyadic multibody formalism for tree-topology systems.** Journal of Guidance, Control and Dynamics. Volume 14, Number 6. pp 1240-1250.

SAYERS, M.W. and KARAMIHAS, S.M. 1996. **Estimation of rideability by analysing longitudinal road profile.** Transportation Research Record, Volume 1536, pp 110-116.

SEBAALY, B., DAVIS, T.G. and MAMLOUK, M.S. 1985. **Dynamics of falling weight deflectometer.** Journal of Transportation Engineering, Volume 111, Number 6, pp 618-632.

SOUSA, J.B., LYSMER, J., CHEN, S. And MONISMITH, C.L. 1988. **Effects of dynamic loads on performance of asphalt concrete pavements.** In: Pavement design. Washington, DC: Transportation Research Board, National Research Council. (Transportation Research Record; 1207) pp 145-168.

STEYN, W.J.vdM. 1997. **Synthesis of vehicle-pavement interaction concepts.** Pretoria: Division for Roads and Transport Technology, CSIR. (Step Report TR-97/046).

STEYN, W.J.vdM. and FISHER, C. 1997. **Report of survey on truck suspension and tyre characteristics: Beitbridge - 2/3 December 1997.** Pretoria: Division for Roads and Transport Technology, CSIR. (Technical Report TR-97/048).

Structural design of flexible pavements for interurban and rural roads. 1996. Pretoria: Committee of Land Transport Officials (COLTO), Department of Transport. (Technical Recommendations for Highways; TRH4).

SWEATMAN, P.F. 1983. **A study of dynamic wheel forces in axle group suspensions of heavy vehicles.** Victoria: Australian Road Research Board. (Special Report 27).

SWEERE, G.T.H. 1990. **Unbound granular bases for roads.** PhD Thesis, Technical University of Delft, Delft.

Terminology related to travelled surface characteristics. 1996. Pennsylvania: American Society for Testing and Materials (ASTM). (E 867).

TFP see The University of Texas at Austin.

The University of Texas at Austin. **Tire force prediction program users guide.**

TIMOSHENKO, S. and GOODIER, J.N. 1951. **Theory of Elasticity.** New York: McGraw-Hill Book Company.

TODD, K.B. and KULAKOWSKI, B.T. 1989. **Simple computer models for predicting ride quality and pavement loading for heavy trucks.** In: Pavement management and rehabilitation. Washington, DC: Transportation Research Board, National Research Council (Transportation Research Record; 1215) pp 137-150.

TRH 4 see Structural design of flexible pavements for interurban and rural roads.

TRH 14 see Guidelines for road construction materials.

ULLIDTZ, P. 1987. **Pavement analysis.** Lyngby, Denmark: Institute of Roads, Transport and Town Planning. (Developments in Civil Engineering Vol. 19).

ULLIDTZ, P. 1997. **Instructor notes on nondestructive pavement analysis.** (Notes for workshop presented at the 8th International Conference on Asphalt Pavements, held in Seattle, Washington, August 10-14 1997). Seattle, Washington.

UZAN, J. 1985. **Characterisation of granular material.** In: Analysis and testing of granular bases and subbases. Washington, DC: transportation Research Board, National Research Council. (Transportation Research Record; 1022) pp 52-59.

VAN NIEKERK, P.E. 1992. **Dynamic loading effects of heavy vehicles on road pavements.** M.Eng Dissertation, University of Pretoria, Pretoria.

WESSELS, L.N. 1996. **National road traffic act (Act 93 of 1996).** Doornfontein: Lex Patria Publishers.

YODER, E.J. and WITCZAK, M.W. 1975. **Principles of pavement design.** 2nd edition, New York: John Wiley and Sons.

ZAFIR, Z., SIDDHARTHAN, R. and SEBAALY, P.E. 1994. **Dynamic pavement-strain histories from moving traffic load.** Journal of Transportation Engineering, Volume 120, Number 5, pp 821-842.

3. STUDY APPROACH

3.1 Introduction

The components of vehicle-pavement interaction were investigated in Chapter 2, with the focus on five themes, to establish current practice and knowledge. In terms of the problem statement, study objectives and scope of this thesis, further development work is performed for two of these themes (vehicle-pavement interaction framework and pavement response). In this chapter the study approach followed for the necessary development and improvements identified is presented.

3.2 Problem Statement and Study Objectives

The problem statement for this thesis states that current pavement design and analysis methods are based on simplifying assumptions regarding traffic loading and material characteristics. Implicit analysis errors that affect the reliability of the pavement analysis, and subsequently affect the cost of a pavement, are caused by these assumptions. These implicit errors must be accommodated for in the final product.

The two primary objectives of this thesis are to develop a practical systems framework to evaluate the various components in vehicle-pavement interaction and to develop and verify a practical approach for the analysis of the transient response of pavement structures to dynamic input loads where appropriate.

A schematic indication of the components of this thesis is shown in Figure 3.1. This figure is used in the remainder of this chapter to indicate the various processes planned and relationships between processes.

3.3 Vehicle-Pavement Interaction Framework

3.3.1 Overview

A thorough framework or system is needed for any problem to understand its holistic nature. In such a framework all the relevant components and factors, and the logical procedure for solving the stated problem should be identified. Once this framework is developed, the components that need focus and attention can be identified.

The main features and limitations of three viewpoints toward vehicle-pavement interaction systems were identified in Section 2.2. It was indicated that a simple unbiased framework for evaluation of vehicle-pavement interaction does not exist in the pavement analysis field. This leads to the main objective of Chapter 4, which is to develop a practical systems framework to evaluate the various components in vehicle-pavement interaction with.

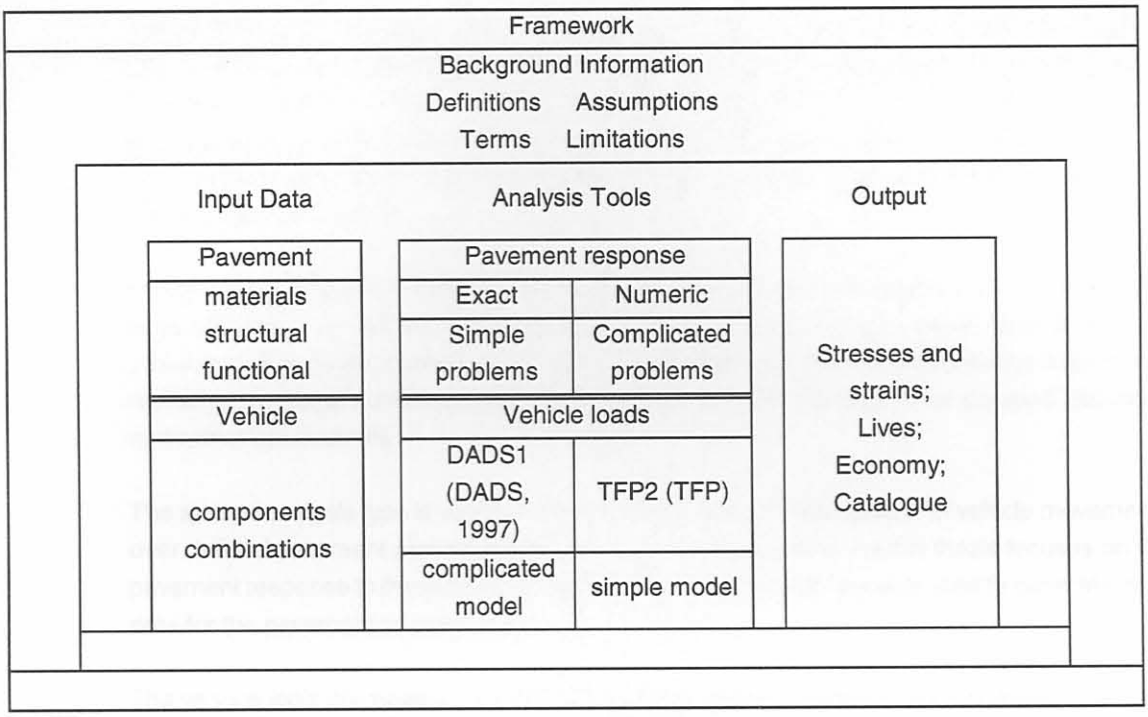


Figure 3.1: **Indication of nominal framework for thesis contents for Chapters 4 to 6.**

In Figure 3.1 it is shown that a nominal framework may consist of 4 main components (based on the references in Section 2.2). These are the Background Information, Input Data, Analysis Tools and Output. The development of the framework forms part of Chapter 4. This includes definitions of terms and other required background information. The input data required for the analyses are also part of this chapter, as the collection and/or development of such data do not form the major part of this thesis.

3.3.2 Process

The process identified for development of the systems framework for vehicle-pavement interaction components consists of the following steps:

a. Development of definitions of relevant concepts and terms for tyre loading and pavement response analysis: Concepts and terms for which confusion exist on their actual definitions are clearly defined. New concepts and terms are defined where necessary. The basic assumptions and limitations of the proposed framework are identified and discussed.

b. Incorporation of the vital components of the various viewpoints into a the framework: The components identified to play a vital role in vehicle-pavement analysis are combined into the framework to be used for the analysis of static and non-static loading and pavement response analyses.

---

[1] Dynamic Analysis and Design System

[2] Tire Force Prediction programme

c. Incorporation of existing input data: The input data required for the tyre loading analyses and pavement response analyses are sourced, shown and discussed. Methods for obtaining the data (i.e. laboratory tests) are also discussed where applicable.

d. Identification of the components of the framework that need further attention in this thesis, and those outside the scope of this thesis: Specific components that receive attention are identified and the possible effects of excluding the other components evaluated.

3.3.3 Output

Steps a to d are addressed in Chapter 4 with a framework populated with current data and techniques as output.

3.4 Pavement Response Analysis Tools

3.4.1 Overview

Various tools are needed to perform the necessary analyses identified in the vehicle-pavement interaction framework. These tools consist of mathematical equations, solvers for the equations and software for performing some of the analyses.

It was shown in Section 2.5 that it is possible to analyse the response of a pavement structure to tyre loading using a static, quasi-transient or full transient pavement response model. Typical pavement structure models and pavement material models for South African pavement materials were presented. Parameters that influence primary pavement response were identified. A need exists for a standardised, user-friendly and accurate method for analysing non-static pavement response to tyre loading.

In Figure 3.1 analysis is shown to be at the centre of the proposed framework. This represents the tools needed to convert the data to user-friendly outputs that may be used in decision-making processes. Two types of analyses are identified for this thesis. The first (and primary) is pavement response analyses. Pavement response analyses methods can broadly be grouped into exact and numerical methods.

The second analysis type is vehicle load analyses. These are simulations of vehicle movements over defined pavement profiles that provide tyre loads as output. As this thesis focuses on the pavement response to these types of loads, the various methods are only used to generate input data for the pavement response analyses.

The various tools are needed to assist in fulfilling the second objective of developing a practical approach to pavement design incorporating vehicle-pavement interaction issues.

3.4.2 Process

The process for developing the pavement response analysis tools involves the following steps:

a. Definition of a multi-layered mathematical method for analysing static pavement response to static and non-static tyre loading: A study is conducted of available multi-layered methods to obtain a procedure by which the static response of a layered pavement to input functions can be determined.

b. Generation of realistic tyre load functions for different pavement and vehicle conditions: The DADS and TFP software are used with the vehicle and pavement fingerprinting information in Sections 2.3 and 2.6 to obtain detailed tyre load functions for specified conditions. These simulations are compared (Chapter 5). The load functions are used in the pavement response analyses in Chapter 6.

c. Definition of the ranges of and methods for determining vital parameters influencing pavement response: The parameters defined in the framework are investigated to determine the parameters most likely to affect the response analyses. Typical ranges for these parameters are defined and the effect of these ranges on the pavement response analyses determined.

d. Definition and verification of analytical methods for analysing non-static pavement response to static and non-static tyre loading for complex load cases: Software is sourced for the analytical analysis of the vehicle-pavement interaction problem. The problem is defined analytically and optimised for analysis. Similar problems are analysed using the multi-layered and analytical methods and the results compared.

3.4.3 Output

The output from the described process includes the standardised multi-layered and numerical analysis methods, a set of tyre loading functions and an understanding of the likely effect of various parameters on the outcome of an analysis. These outputs are presented in Chapter 6.

3.5 Evaluation

3.5.1 Overview

A tool is only worth its cost if the ultimate effect of its application justifies its use. It thus needs to be shown that the tools developed in this thesis will cause a cost-effective justification for their implementation in relation to the current tools being used.

The last objective of this thesis is to evaluate the effect of transient pavement response analysis on pavement design. This involves a comparison of the results of traditional pavement analyses with that using the proposed framework and tools.

In Figure 3.1 the final part of the proposed framework consists of the output. This contains all of the results from the various analyses. The output can take on various forms depending on the level of analysis and user requirements. In Chapter 7 the focus is on providing the output in a format familiar to general pavement engineers in South Africa, and showing examples of using the proposed analysis procedures. The final output of the thesis is a guideline for effective use of the proposed analysis methods for non-static pavement response to various load conditions.

3.5.2 Process

The process for performing the evaluation of the effectiveness of the proposed framework consists of the following steps:

a. Development of guidelines for indicating the process of including non-static tyre loading effects in a pavement analysis: Static and non-static pavement response analyses of various load functions are performed and the results compared.

b. Comparison of the results of static and non-static response analyses: A pavement structure is analysed using the various tyre loading and pavement response analysis procedures developed and the s results compared to evaluate the effect of the proposed non-static methods.

3.5.3 Output

The outputs of these analyses are the proposed guidelines. These are provided in Chapter 7 in a format compatible with the TRH4 (1996) manual.

3.6 Conclusions

A study approach for dealing with the problem statement identified for this thesis is discussed. The study approach consists of development of a framework for vehicle-pavement interaction analyses, population of the framework with existing data, development of tools for performing static and non-static pavement response analyses to varying tyre loading conditions, and verification of the effect of incorporating non-static pavement response analyses in pavement design.

3.7 References

DADS. 1997. **Dynamic analysis and design system.** User's guide. Revision 8.5.

Structural design of flexible pavements for interurban and rural roads. 1996. Pretoria: Committee of Land Transport Officials (COLTO), Department of Transport. (Technical Recommendations for Highways; TRH4).

TFP see The University of Texas at Austin.

The University of Texas at Austin. **Tire force prediction program users guide.**

TRH 4 see Structural design of flexible pavements for interurban and rural roads.

4. VEHICLE-PAVEMENT INTERACTION FRAMEWORK

4.1 Introduction

The development of a vehicle-pavement interaction framework was identified as one of the objectives of this thesis. In Section 2.2 the various existing models for describing vehicle-pavement interactions were discussed and evaluated. The issues that were identified were:

a. Traditionally pavement and vehicle engineers view the vehicle-pavement interaction system with bias towards their own knowledge and experience;
b. A clear distinction does not exist between pavement behaviour and performance issues;
c. It is possible to use behavioural models at various technology and/or complexity levels in the same analysis. The ultimate effect (beneficial or not) of such combinations is not clear (i.e. least denominator effect).

The objective of this chapter is to provide a practical framework for use in vehicle-pavement interaction studies. The chapter includes various definitions and terminology, the developed framework, an investigation of the effect of technology levels on the framework and typical assumptions and input data.

The following is explicitly excluded from this chapter:

a. Detailed information regarding vehicular models and data (this does not form part of the scope of this thesis);
b. Detailed information regarding pavement behavioural models and data (this is covered in Chapter 6);
c. Detailed information regarding decision criteria (this does not form part of the scope of this thesis), and
d. Detailed discussion regarding the effects of external factors (i.e. the socio-economic environment) on the vehicle-pavement interaction framework (this does not form part of the scope of this thesis).

4.2 Definitions and Terminology

4.2.1 Introduction

Some concepts in vehicle-pavement interaction are not clearly defined or understood by practitioners in the different fields of interest. Definitions for the concepts of importance in this thesis are provided below.

4.2.2 Vehicular definitions and terminology

Generically tyre loads vary in two distinct ways. The first is the variation of load between different vehicles travelling on a pavement, while the second is the varying loads applied by a specific vehicle (and axle) along the pavement. A clear definition regarding the various types of tyre loading possible on a pavement, is needed both for vehicle and pavement engineers.

The first type of variation has traditionally been accommodated in pavement analysis through the use of equivalent load concepts. The traditional power law for estimation of the damage caused by axle loads was developed mainly after the AASHO road test (HRB, 1962) and subsequently applied internationally. Later research indicated that the value of the exponent of the power law could vary substantially, depending on the type of pavement being trafficked (Horak, 1992; TRH4, 1996).

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). The use of the term dynamic in pavement analysis can, however, cause confusion. A load with a constant magnitude that is moving along a pavement, and a load that is stationary along the length of a pavement but varying with respect to time in load magnitude, can both be defined as dynamic. Both these loads also cause a dynamic response from the pavement. The author proposes the following definitions for four types of tyre loading. These are perceived to cover all types of tyre pavement loading (Figure 4.1).

a. 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);
b. 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);
c. 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), and
d. 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).

The convention defined for description of the load conditions is that, for tyre loads the tyre is used as the reference point. This causes the vehicle to experience the pavement surface as a time-dependent input. The load history is defined as a periodic excitation that can be represented by a Fourier series (Dimarogonas, 1996).

Typical examples of these four categories of load conditions are:

- A parked vehicle (Static Load);
- A typical Accelerated Pavement Testing device load (i.e. HVS Mark III) (Moving Constant Load);
- A Falling Weight Deflectometer (FWD) (Dynamic Load), and
- A real vehicle driving on a real pavement (Moving Dynamic Load).

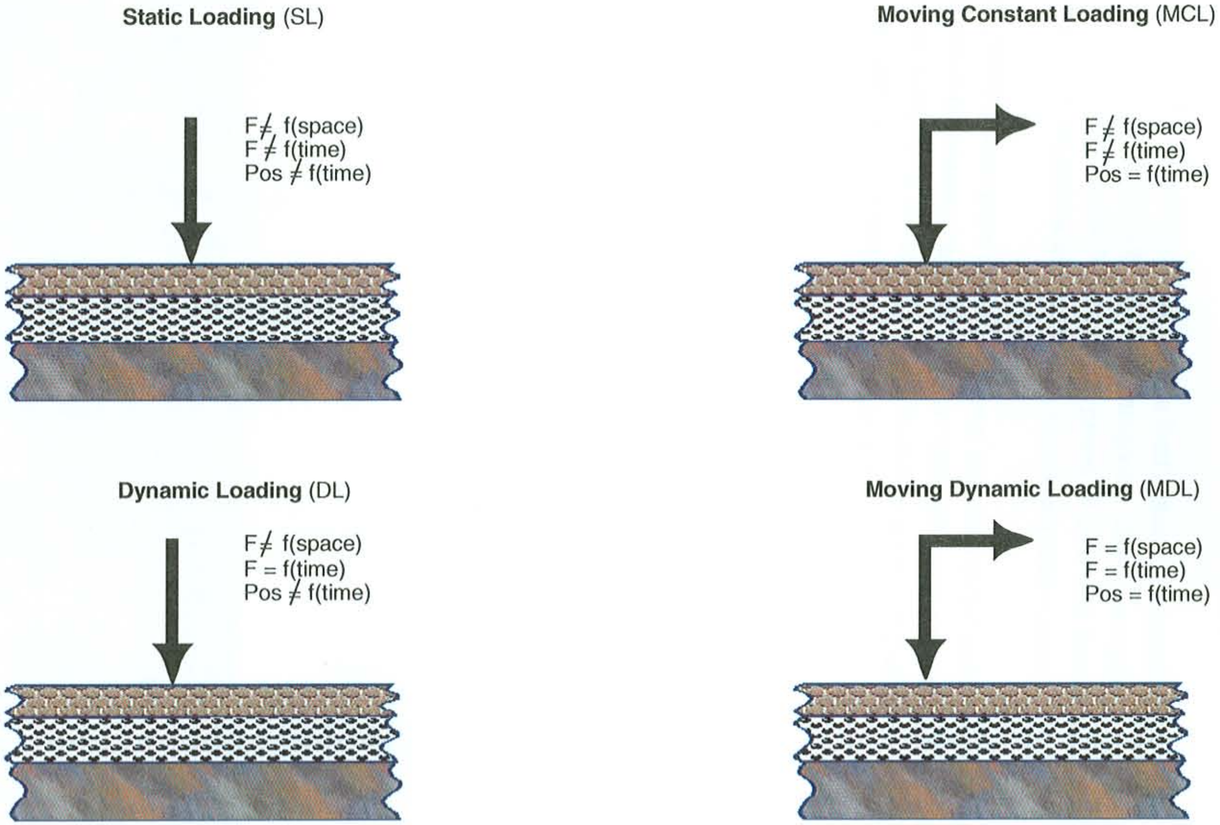


Figure 4.1: **Four types of loading modes.**

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.

4.2.3 Pavement definitions and terminology

Two types of pavement response analysis can be defined. These are (Figure 4.2):

a. Static Response Analysis (stresses, strains and deflections are independent of time but dependent of load position), and
b. Transient Response Analysis (stresses, strains and deflections are dependent of time and of load position).

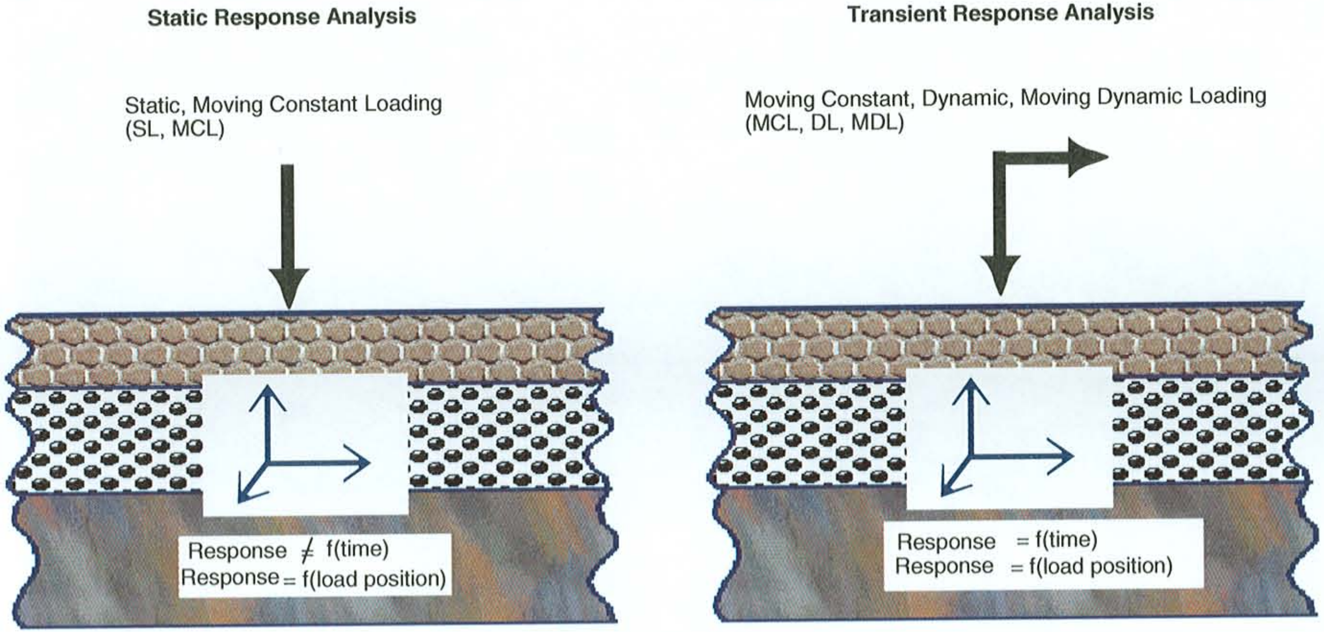
Ideally, the type of loading applied should dictate the response analysis of the pavement. Thus Static Response Analysis should be performed for time-independent loading (i.e. Static Loading) while Transient Response Analysis should be performed for time-dependent loading (i.e. Moving Constant, Dynamic and Moving Dynamic Loading).

Quasi-transient response analysis is defined as Transient Response Analysis in terms of these definitions, as the response analysis is essentially time dependent (although calculations are performed in the spatial domain and not in the time domain).

The convention defined for description of the load conditions for pavement response analysis purposes is that, a specific position in the pavement structure is defined as the reference point. Thus the pavement experiences the tyre loading as time-dependent input. This convention focuses the attention of the engineer on the effect of the load at a specific position in the pavement. The engineer should not try to 'run with the tyre' when analysing the pavement response, but rather investigate the effect of an approaching and departing load on a specific position. The objective of the pavement engineer should be, to determine how strong each discrete point in the pavement should be to withstand damage as long as economically possible.

From a vibrational analysis viewpoint the load history on a specific location of the pavement is defined as a nonperiodic excitation (Dimarogonas, 1996). A nonperiodic excitation usually has the form of a force that acts for a specific period of time and then stops, or it can have longer durations and magnitude with known but nonperiodic time histories.

Ullidtz (1987) defines pavement behaviour or response as the critical stresses or strains in each of the pavement structure layers. Pavement performance is defined as the future functional and structural condition of the pavement. Performance is predicted using an empirical relationship between response (behaviour) and the rate of deterioration.



Static Response Analysis

Transient Response Analysis

Figure 4.2: **Two types of response modes.**

4.3 Modular Vehicle-Pavement Interaction Framework

4.3.1 Introduction

In Section 2.2 various available vehicle-pavement interaction frameworks were evaluated. From this it was synthesised that pavement and vehicle engineers view vehicle-pavement interaction with bias towards their own knowledge and experience and that a clear distinction does not exist between pavement behaviour and performance models in vehicle-pavement interaction frameworks. Further, the ultimate effect of using behavioural models at various technology levels in the same analysis is not quantified.

In this section the basic vehicle-pavement interaction frameworks are used as the basis for a modular vehicle-pavement interaction framework. The objective is to have a standard on which the type of information and procedures (i.e. behaviour or performance data), which are necessary to perform a transient pavement response analysis for dynamic tyre loads, can be defined. It further assists in establishing current areas in need of improved analysis techniques or data.

4.3.2 Vehicle-pavement interaction components and interfaces

The main limitation with the current vehicle-pavement interaction systems appears to be the lack of consideration for those factors that the analyst is unfamiliar with. These are generally the vehicular aspects for the pavement engineer and the pavement aspects for the vehicle engineer.

A solution to this problem would be to identify and incorporate all the various components of the vehicle-pavement interaction system into a modular framework. The various component modules are populated with typical behaviour models and the interfaces between these components defined. Such a framework would allow the analyst to focus attention on those aspects with which he is familiar, improving the analysis in these areas, and then make use of the best-proven technology in those areas where he is not familiar.

There are four standard components that occur in the majority of the vehicle-pavement interaction frameworks evaluated (Haas et al, 1994; Collop and Cebon, 1995a, 1995b; Divine, 1997). These are:

a. The pavement profile;
b. The vehicle;
c. The pavement structure, and
d. The decision making process.

These four components are viewed as the main components, as they represent:

a. The cause of the problem (pavement profile);
b. The load history generator (the vehicle);
c. The component on which the forces are exerted (the pavement structure), and
d. The final evaluation criteria (decision making process).

Traditionally the pavement profile and structure were the domain of the pavement engineer, the vehicle the domain of the vehicle engineer and the decision making criteria the domain of the transportation engineer and administrators.

Each of these components can be divided into sub-components. They each have specific generic input and output parameters and algorithms. Compilation of such a generic framework would enable data and/or techniques of different levels of technology to be used in the framework as they become available, and would not tie the framework to a specific set of data and/or techniques.

The specific input and output parameters and algorithm descriptions for each of the identified components are shown in Table 4.1.

The focus of this thesis is on:

a. The pavement profile;
b. General tyre load histories, and
c. Pavement response analysis;

The remaining components are not part of the focus for this thesis, although this does not deter from their importance in the framework.

None of the actions described in Table 4.1 occur in isolation. The general socio-economic, natural and political environment for which the specific vehicle-pavement interaction analysis is done affect the input data, behavioural models and evaluation criteria. For this thesis specific emphasis is not focussed on these external environmental issues, although their importance and possible effect on vehicle-pavement interaction analyses are not ignored.

For instance, the economic and political climate in a region may affect the type of vehicle and goods transported on a pavement, while the natural environment affects the behaviour of the various pavement materials.

The input data for each component have specific practical ranges in which it can occur. These ranges may depend on the geographical region, season, climate or current legislation. Different commodities are transported in different geographical regions, and thus high-density low volume loads may be more frequent in one area with low-density high volume loads in other areas. Seasonal changes in input parameters may be caused by the changes in vehicle types and loads during some seasons, while climatic information such as temperature and moisture may affect the pavement structure. Legislation has a direct effect on the type of vehicle and vehicle characteristics occurring on a pavement.

Variations in these parameters influence the input data, and thus specification of the actual conditions for which analyses are performed is vital. The influence of various parameters on each other may also be affected by such differences in input data ranges.

Table 4.1: Nominal input, output and procedural parameters for each of the identified components in the generic vehicle-pavement interaction framework.

INPUT PARAMETERS	COMPONENT MODULE	OUTPUT PARAMETERS
PAVEMENT PROFILE		
vertical pavement profile	pavement roughness statistic algorithms	verified vertical pavement profile; pavement roughness index; spectral classification
	spectral analysis	
VEHICLE		
vertical pavement profile	tyres	3-dimensional movement at axle
3-dimensional movement at axle	suspension	3-dimensional movement in vehicle structure
	configuration, dimensions	
	operational conditions (speed, load, load positioning, linear / corner movement, acceleration / constant / deceleration)	
3-dimensional movement in vehicle structure	vehicle model	3-dimensional tyre-pavement contact stress (load history)
PAVEMENT STRUCTURE		
3-dimensional tyre-pavement contact stress (load history)	pavement response / behaviour models	stresses, strains and deflections
stresses, strains and deflections	pavement performance models (transfer functions)	estimated pavement / layer lives
DECISION MAKING PROCESS		
estimated pavement / layer lives	Economic models	economic life of pavement
economic life of pavement	decision making criteria	acceptance decision

Ullidtz (1987) indicated the difference between behaviour and performance in pavement engineering. The behaviour indicates the immediate response (critical stresses and strains) of the pavement structure to a load, while the performance indicates the future (long term) condition of the pavement. The same argument may be used to define any momentary effects (response to input data) by a component as behavioural or response effects and the long-term effects as performance effects. In this definition the momentary response of vehicle suspension to unevenness on the pavement surface will be defined as behaviour or response, while the long-term deterioration of the suspension characteristics due to constant unevenness on the pavement surface be defined as performance.

4.3.3 Parameter interaction

The various components in the vehicle-pavement interaction framework (Table 4.1) interact with each other in specific manners. These manners depend on the input data, behavioural models used to model the specific components' responses to input data and the operational conditions.

The framework is essentially defined as a linear framework in which each of the components only affects the components following it in the framework. This is true for behavioural studies. For performance studies components may implicitly affect components preceding it in the framework as the output from the framework will again affect the input data to the framework for iterative calculations.

The types of interactions may range from no influence to linear interactions to non-linear interaction functions. As time-dependent input data and response functions are modelled, frequency dependent effects may also be observed. For the purposes of this thesis it is important to define the nominal interactions that are possible between parameters. Specific interaction data will be developed from the actual analyses later in this thesis, and will depend on models and data used as indicated.

The first interaction is that between the pavement profile and the vehicle tyre. This interaction is dependent on the level of pavement roughness (input data), the tyre characteristics (behaviour model) and operational conditions (i.e. speed and tyre inflation pressure). The output data are forces exerted between the tyre and the suspension. Note that this is currently not the interaction between the tyre and the pavement structure, this is thus the input provided from the vertical pavement profile to the tyre, although this is essentially happening together with the loads that are exerted on the pavement structure.

The next few interactions may either be implicitly included in a nominal vehicle model or each modelled individually. These are the interactions between the tyre and the suspension, the suspension and the vehicle body and the vehicle body and the load. In this thesis less focus is put on these interactions, and they are treated as part of a specific vehicular simulation model. The input data are the tyre-suspension forces, and the output data tyre load histories. The load histories are part of the interaction between the tyres and the pavement surface. This is typically one of the areas where the use of the modular framework, assist the pavement engineer in providing detailed tyre load histories, with pavement profiles being the only detailed input data and realistic, existing vehicle models providing the 'black box' for calculating detailed load histories.

The next interaction is that between the tyres and pavement structure. This interaction depends on the load histories (input data), pavement behavioural models and material properties (i.e. material types, densities and moisture conditions). The outputs from this interaction are stresses and strains in the pavement structure.

Finally the stresses and strains (behavioural data) are converted to performance data using appropriate transfer functions, and to economic data using economic models.

The continuous interaction between vehicle and pavement cause the ultimate effect of the applied load histories on the pavement to influence the pavement profile, and thus the whole process changes continuously as pavement profile, vehicle and pavement structure characteristics change with time. When the focus is on the immediate response of any of the components to inputs, the effect is termed behaviour or response while performance defines the long-term interaction and changes in the component.

Based on this explanation of the possible interactions between the various components the following can be postulated:

a. Direct interactions occur between components that are in contact with each other;
b. As all components in the framework are ultimately in contact with each other, no component is totally independent of changes in any other component;
c. The effects of changes in any component on the behaviour of any other component depend on factors such as, the number and type of components between the two components in question and the sensitivity of the affected component for changes in input data;
d. The effects of changes in input data values or ranges should be less than the effects of changes in behavioural models, as the latter may change the whole response mode of the component (i.e. linear versus non-linear response models);
e. Specific effects of components on each other can only be evaluated for a specific set of behavioural models and data.

4.4 Technology Levels

Technological levels are defined in this thesis as the different levels of complexity found in the various data, models and decision criteria applicable to a specific problem. Essentially, the technology level of a problem may be basic, intermediate or advanced.

Basic technology levels define those technologies where the input data, behavioural models and outputs are simple, and general trends may be deduced from the analysis. A specific technology may be at a basic level due to reasons such as a lack of specialised input data, lack of computational capacity, lack of more detailed behavioural models, or lack of financial or resource capacity. In many instances a basic technology provide a sufficiently acceptable answer to a specific problem, and the application of more resources would not increase the final decision criteria accuracy.

Intermediate technology levels define those technologies where the input data, behavioural models and outputs are more detailed, and interaction between various parameters may be observed. Intermediate technologies would also be those technologies for which some aspects are advanced (i.e. input data), but due to limitations in other parameters (i.e. behavioural models) the overall process cannot benefit from the advanced parameters.

Advanced technology levels define those technologies where the input data, behavioural models and outputs are as detailed as physically and practically possible. Basic research can be performed on this level, and the confidence in the output is high. However, generally an increase in technology level to advanced would also cause a subsequent increase in capacity and resources.

In Table 4.2 a typical indication of the various technology levels for vehicle-pavement interaction is shown. Although this is may be a subjective analysis of the field, it provides a basic background to the concept.

One of the first questions that develop from a careful analysis of Table 4.2 and the definitions of the various technology levels, is what the ultimate effect of combining technologies from different levels in an analysis would be (the smallest common denominator or largest common product question) i.e. is there any benefit in using an advanced vehicle model with a basic pavement model.

There are some obvious combinations that would not be feasible. This would typically be where the input data from the basic technology are insufficient to enable the advanced technology's behavioural model to be operational, or where the input data from an advanced technology would be too complicated for application in the basic technology behavioural model.

It may generally be argued that the higher the quality of any one component in a system, the higher the quality of the whole system should be. However, such higher quality comes at a price, and if the effect is not observable in the ultimate answer of the analysis, such investments may be wasted, and a false sense of higher trust in the analysis may have been caused. The increased quality is also only beneficial if it can affect the quality of the other components in the system.

Combinations between technology levels should preferably be between similar or adjacent (i.e. basic and intermediate or intermediate and advanced technology levels). The output and input data from the two technology levels should be compatible.

It can be expected that in certain cases the use of more advanced technology levels in the analysis may increase the value of the general outcome of the analysis. This is true where the data / model from the higher technology level component increase confidence in the other analyses. The increased confidence may stem from simply increased awareness by the user for the possible effects of data or model ranges, to real increased benefits in the output data.

Where doubt exists regarding the real interaction between two components on different technology levels, similar technology levels should rather be used in an analysis. Where the outcome from a more advanced technology level introduces data that cannot be accounted for or used in the following technology levels, similar technology levels should be used. Exclusion of such additional data from further analyses may skew the data used in subsequent analyses.

It is important to realise the effect of increased technology levels on the possible error, costs and efforts needed in performing an analysis. In Figure 4.3 a schematic indication of the possible relationship between these factors are shown. As the technology level increases, the cost of data collection and analysis generally increase. The effort needed to perform a correct analysis at the higher technology levels also increase. The possible analysis error should however decrease with increasing technology level.

Table 4.2: **Technology levels for vehicle-pavement interaction analyses as defined in this thesis.**

TECHNOLOGY LEVEL	LONGITUDINAL PAVEMENT PROFILE	VEHICLE	PAVEMENT STRUCTURE	DECISION MAKING PROCESS
Advanced technology	Full spectral influence of longitudinal pavement profile incorporated.	Detailed vehicle and component models in which characteristics and operational conditions cause different effects from similar components included. Moving Dynamic Loads incorporated.	Full Transient Response analysis using detailed non-linear non-homogeneous material models incorporating variations in material properties and time-dependent behaviour. Factors such as soil suction may be incorporated in material models.	Detailed algorithms incorporating external environmental factors and long-term effects.
Intermediate technology	IRI type of pavement roughness statistic.	Basic vehicle motions and improved operational conditions included. Moving Dynamic Loads may be considered.	Non-linear effects and time-dependent effects may be included. Issues such as non-uniform tyre-pavement contact stresses may be included.	Detailed process incorporating limited external factors and ranking of decisions based on scenario analysis.
Basic technology	No input, pavement roughness does not play a role.	No input, vehicle components are not considered and equivalent load levels are used as input to pavement analysis. Only Moving Constant Loads analysed.	Linear elastic homogeneous isotropic analysis with typical material models. Static Response analysis only.	Basic process providing general life-cycle costing and pavement class information.

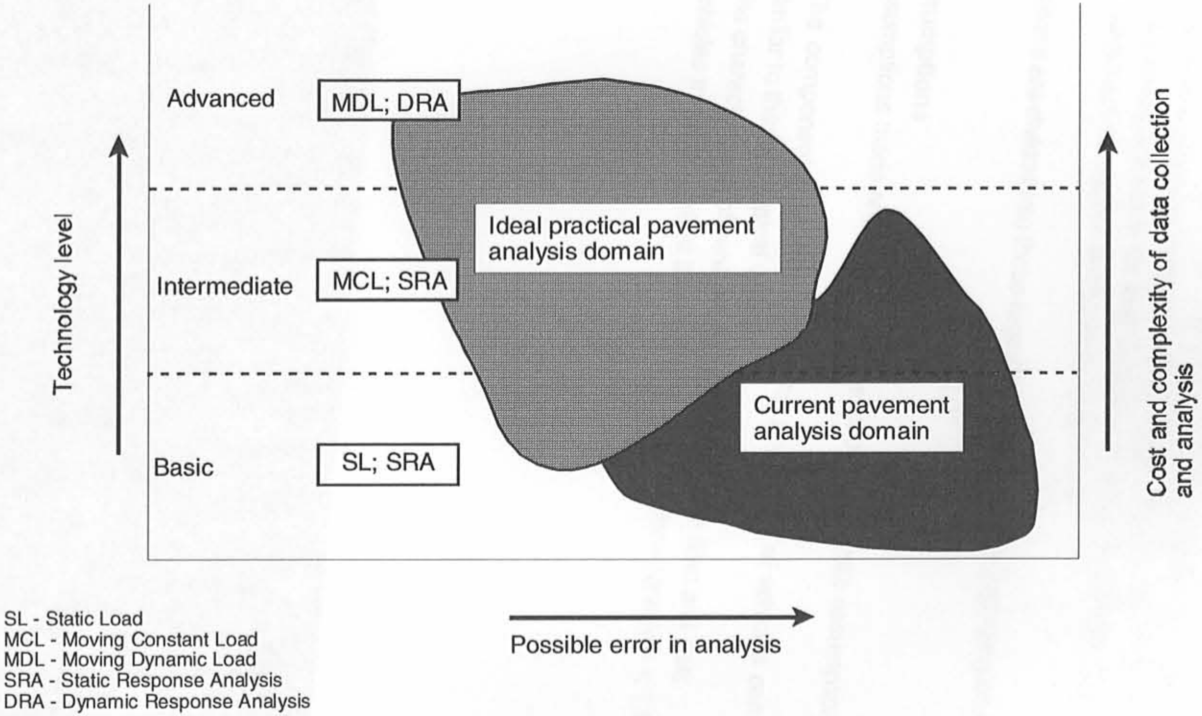


Figure 4.3: **Schematic indication of the possible relationship between the possible error, costs and efforts needed in performing an analysis for various technology levels defined in this thesis.**

Two domains are shown in Figure 4.3. These are the author's estimate of the current pavement analysis domain and of an ideal practical pavement analysis domain. The current domain is located mainly in the basic technology level with a relatively high possible analysis error and relatively low cost and complexity associated with data collection and analysis. The ideal practical domain is situated mainly in the intermediate technology level with a relatively lower possible analysis error but an associated higher cost and complexity for data collection and analysis.

It is the opinion of the author that this ideal domain should enable a more realistic analysis than currently (i.e. including more realistic traffic and material response characterisation) with an acceptable increase in effort, cost and complexity. Possible benefits of such a move should be more optimal use of available material resources and allowance for more optimal pavement friendly vehicles to be accommodated in the vehicle-pavement interaction analysis.

4.5 Assumptions

4.5.1 Introduction

Various assumptions are made when analyses are performed. This is done to cater for those conditions and parameters for which specific data cannot be collected, or where the available models do not cater for specific analyses. Assumptions can be used as long as they are valid and their use well motivated.

Assumptions regarding the following aspects were made in this thesis:

- input data;
- vehicular properties;
- pavement properties;
- analysis options;
- transfer functions, and
- material constitutive laws and models.

It is appreciated that some of the assumptions cause some effects of vehicle-pavement interaction to be neglected. However, as these issues typically fall outside the scope of this thesis, recommendations are made for their inclusion in follow-up studies, once the need for dynamic vehicle-pavement interaction analyses is established.

Assumptions are divided into those regarding data and those regarding analysis techniques in this thesis.

4.5.2 Data assumptions

In the assumptions made regarding data, the following specific assumptions are made:

a. The component characteristics of the population of vehicles can be assumed to be similar to that of a typical vehicle;
b. The characteristics of vehicles do not change with time and use;
c. Vehicles travel in straight lines on level road sections (gradient < 1,5 per cent);

d. The component characteristics of the population of pavements can be assumed to be similar to that of a typical pavement, and
e. The measured and published material parameters used are valid representatives for the typical materials.

Assumption a is made after the three most typical heavy vehicles used on South African pavements were identified (Section 2.6.2). For the purpose of the vehicle simulations a typical vehicle had to be selected to obtain the dimensions and component characteristics to be used in the simulations. Specifications from three real vehicles were used for this purpose (Gilliomee, 1999). It is accepted that variations in these characteristics may affect the results of the pavement response analyses. However, it falls outside the scope of this thesis to evaluate the effect of such variations. It is recommended that such an investigation be performed after the need for dynamic vehicle-pavement interactions was established.

Assumption b is made as it is known that the characteristics of components change with time (i.e. the stiffness of a suspension system). It would however become a major part of the investigation to include such deterioration, and therefore the component characteristics were selected to be representative of operational (not new) components. Effects of vehicle component deterioration on pavement response should be addressed after the need for dynamic vehicle-pavement interactions was established.

Assumption c is made as different forces are developed when a vehicle travels in a straight line than when it travels around a corner. Further, characteristics such as the radius and camber of the corner, and the gradient of the road also affect these forces. As this is the first study of its kind for South African conditions, only linear movement is assumed. The gradients in the road sections used for the analyses range between 0,3 and 1,5 per cent. A study into the effects of travel around corners is recommended as further work in this thesis.

Assumption d is similar to Assumption 1, but applicable to pavements. Again, all the relevant variations in component characteristics cannot be included in the study without increasing the extent to a large degree. Three typical pavement structures were selected (Section 2.6.3) and typical component characteristics for these structures used in the analysis. It is recommended that the effect of variations in pavement characteristics on pavement response analysis be performed after the need for dynamic vehicle-pavement interactions was established.

Assumption e is made as the scope and budget for this thesis did not allow all material properties to be measured in the laboratory. Limited laboratory test data could be used, and some published material properties had to be used. This was done specifically in those areas where possible variations in these data were not critical to the study, or where such data are generally agreed on as typical by the pavement engineering community. Again, the effect of pavement material changes on pavement response analysis should be investigated after the need for dynamic vehicle-pavement interactions was established.

4.5.3 Analysis assumptions

In the assumptions made regarding analyses, the following specific assumptions are made:

a. The selected analysis (or simulation) options are representative of typical analysis (or simulation) options;
b. The current SAMDM transfer functions for pavement structures (developed for static loading conditions and response analyses) are valid;
c. The constitutive laws selected for each of the models are valid for the conditions in which they are used;
d. Vehicles travel on flat slopes only, and no significant uphill or downhill travel are part of the analysis
e. The full effects of pavement roughness can be experienced from a pavement section length of 6 km;
f. All material calculations are done in the total stress mode, and
g. All analysis of material response is performed in the linear elastic mode of response, and no non-linear elastic effects are investigated.

Assumption a is made as many analysis and simulation methods are available to analyse pavement structures and simulate vehicle dynamics. Although many of these methods are similar, small differences in approaches and parameters used can lead to different outcomes for the same nominal data sets and conditions. All efforts were made to ensure that the methods used in this thesis are typical and do not suffer from blatant errors. It is also not within the scope of this thesis to investigate in detail the effect of different methods on the vehicle-pavement interaction issue.

Assumption b is made specifically for those transfer functions used to convert pavement structure stresses, strains and deflections into pavement lives. The transfer functions developed for South African materials and conditions were all developed using static equivalent load conditions, and many using HVS results (Theyse et al, 1996). It would be valid to assume that transfer functions using dynamic load data and transient pavement response data may be different from these current transfer functions. However, the development of transfer functions is a major and costly effort. It is recommended that such an investigation be done upon successful indication that the effect of dynamic loads and pavement response is of such a nature that these types of analyses should be performed as routine. The current SAMDM transfer functions were developed based on linear elastic material models, and the material models used for all the pavement response analyses in this thesis are also linear elastic. It is thus assumed that these transfer functions can be used as an initial indication of pavement lives.

Assumption c is made as many different constitutive laws exist for pavement materials. Most of these laws are focussed on analysis of specific aspects of the behaviour of a material. The constitutive laws used in this thesis are deemed to be of sufficient quality to enable a thorough and valid analysis of the pavement response.

Assumption d is made to simplify the initial analyses that are performed for this thesis. As this thesis forms the reference for further work into vehicle-pavement interaction, it should provide base-line information for further studies to build on.

Assumption e is made as a specific minimum length of pavement of similar roughness is required to ensure that the dynamic effects generated in the vehicle have stabilised. Studies have shown this length of pavement to be sufficient to ensure that the analysis speeds can be reached and that stable dynamic response can be obtained (Gilliomee, 1999). It also becomes increasingly difficult to obtain long lengths of pavement with very rough pavement profiles.

Assumption f is made as it is known that geotechnical calculations performed using total and effective stresses are not similar. However, lack of information on suction forces and saturation levels in pavement materials currently precludes a detailed incorporation of effective stress analyses into the pavement response analyses domain. The effect of such effective stresses on pavement response should be investigated further.

Assumption g is made as the currently available non-linear material models and analysis methods (i.e. FEM) are very time-consuming with analyses taking days rather than hours to be completed. In the view of the objectives of this thesis, such non-linear analyses are thus excluded, although the inclusion of these models and analyses are recommended for further work.

There can be speculation regarding the effects of the various assumptions. However, without a detailed understanding of the issues implicitly included in the assumptions, and therefore the option to include the assumption into the analysis, such speculation may be premature. Therefore, some guidelines are provided after the analyses in Chapter 7 regarding some of the assumptions, but it is recommended that detailed attention should be given to those assumptions that appear relevant in separate studies.

Speculation may also be performed on accommodation of the specific assumptions (i.e. how to get rid of them without including them in the analyses). However, this can also only be done after the initial analyses have been performed, and thus such a brief discussion is provided in Chapter 7.

4.6 Input Data

4.6.1 Vehicular input data

The input data used for the tyre load history simulations consist of dimensional, component characteristic and operational data. The dimensional and component characteristic data were collected from actual vehicles and components which conformed to the typical vehicle and component types identified as the most frequently used on heavy vehicles on South African roads (Section 2.6.2). These data are summarised in Appendix A.

The operational data (i.e. speed and loads) were selected based on data from permanent weigh-in-motion stations and also to enable a thorough variation in values to enable trends in the results to be visible.

Three speeds were selected for the simulations. These are 40 km/h, 80 km/h and 100 km/h. These speeds 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 maximum speed of 100 km/h was also calculated as the maximum attainable speed for the specific vehicle combinations selected in this thesis. In the simulation the vehicles accelerate from rest to the indicated speed, maintain this speed for at least 2 km and then decelerate to rest. The acceleration, constant speed and deceleration sections of data are first used individually in the analysis, and then compared to establish relationships between the three types of data.

Three load conditions were selected for the simulations. These are an empty load, a legal maximum load and an overload equal to that found for typical South African conditions (Nordengen, 1999). The degree (i.e. mass) of overloading used is 10 per cent of the legal load. The extent (number of overloaded vehicles) of overloading is assumed to be 30 per cent (Nordengen, 1999). These figures are not selected for a specific area in South Africa, but as a nominal value to be used for this thesis. It is recommended that detailed studies incorporating specific data for various regions into dynamic vehicle-pavement interaction be performed once the basic techniques are developed. These loads are assumed to be distributed evenly over the length of the vehicles for this thesis. The overload portion (10 %) is distributed evenly over all non-steering axles. It is recommended that further work be conducted where loads that are not evenly distributed (leading to some axles being loaded higher than others) are used in the vehicle simulations and pavement response analyses.

4.6.2 Pavement input data

The input data used for the vehicle simulations consisted of pavement profiles, while material types, material characteristics, engineering properties of materials, dimensional and operational data were used in the pavement response analyses.

The pavement profile data consisted of the pavement roughnesses of three typical pavements. Typical national pavement roughnesses in South Africa were shown to be around 2,5 IRI (Kannemeyer, 1998). For rural and provincial pavements this is believed to be higher, although specific figures are not readily available. The pavement roughness data were used as input to the vehicle simulations. It was sourced from actual High Speed Profilometer (HSP) data records.

It was decided to use real pavement data as opposed to artificially generated pavement sections for the vehicle simulations. This should ensure realistic response from the vehicles to the pavement profiles.

The prerequisite for these data were that at least 6,0 km of uniform data were needed to enable the vehicle simulations to be performed on uniform pavement roughness sections. Although difficulty was experienced in obtaining such data, three sections of roughness 1,2 HRI, 3,1 HRI and 5,3 HRI were identified. To ensure the uniformity of these sections, Power Spectral Density (PSD) analyses were performed on the pavement profile data. Details of these analyses (specific procedures, software and parameters) are shown in Appendix B.

The PSD analyses indicated the three pavement sections to be categorised as shown in Table 4.3 using the ISO 8608 procedure (ISO, 1995). International Roughness Index (IRI), Half-car Roughness Index (HRI) , Truck Response to Roughness Index (TRRI) and Half Truck Response to Roughness Index (HTRRI) roughnesses for the three test sections were calculated and shown in Table 4.3. (Refer to Section 2.3 for definitions of these indices).

Table 4.3: **ISO (1995) classification and IRI, HRI, TRRI and HTRRI values of three pavement sections used in vehicle simulations.**

PARAMETER	PAVEMENT IDENTIFICATION AND DATA		
	SMOOTH (S)	AVERAGE (A)	ROUGH (R)
ISO classification	A	B/C	C/D
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 [[m/s^2/m]L;R*	1,8; 1,8	4,8; 5,5	9,2; 6,6
HTRRI [m/s^2/m]	1,5	3,9	6,3

* Left and Right wheeltracks

The ISO classification (ISO, 1995) for the three pavements is shown in Figure 4.3. The displacement Power Spectral Density (PSD) plot shows the Displacement PSD versus spatial frequency. Dominant peaks on this graph indicate dominant spatial frequencies in the pavement profile data. As relatively little such peaks occur in the data investigated no specific cause (i.e. artificial construction faults) can result in the specific roughness on the pavements selected.

The spatial frequencies occurring at body bounce (approximately 3 Hz) and axle hop (approximately 15 Hz) at the three speeds selected for the analyses in this thesis, are shown in Figure 4.4. All the lower frequencies (body bounce) occur at positions where the displacement power spectral density (DPSD) indicates a marked difference between the three pavement sections. However, the higher frequencies (axle hop) occur at DPSD values where less difference exist between the DPSD values. This is partly caused by the dominance of higher frequencies in the DPSD analysis. As the body bounce mode of Moving Dynamic Loading (MDL) is the more dominant factor in MDL, due to its higher magnitude, this cause less of a concern for the various analyses. Pavement sections with different profiles were also investigated and it was shown that this convergence of DPSD values at higher spatial frequencies (i.e. > 1,00 c/m) is typical for all pavement profiles investigated.

The pavement structure data consist of the structural information for three typical pavements. No connection exists between the three pavements selected for the pavement profiles and the three pavements selected for the pavement structural analysis. The first three pavements are real pavements while the latter are typical pavement structures selected from TRH4 (1996).

These structures were obtained from the TRH4 catalogue, after determining the most typical pavement structures from provincial and national Departments of Transport databases. The three structures are shown in Table 2.8. This data consist of dimensional data (layer thicknesses), material types and engineering properties of the materials (i.e. various moduli).

The dimensional data consist of the layer thicknesses for the various materials and the expected variances in these thicknesses. This data, together with the total pavement thicknesses and the expected Coefficient of Variance (CoV) in layer thicknesses are shown in Table 4.4. Information on layer thickness variation was obtained from Jooste (1998). The typical CoV of layer thickness for all layers were 15 per cent.

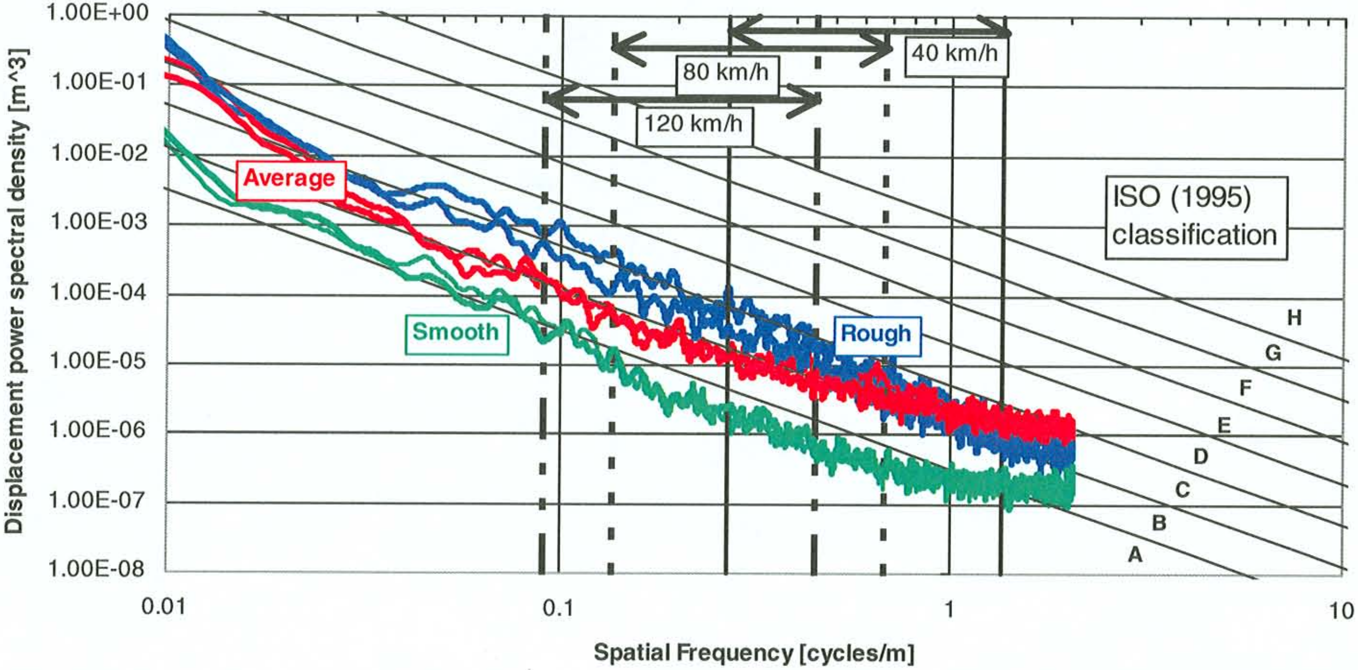


Figure 4.4: Displacement Power Spectral Densities (DPSDs) on ISO classification for all three pavements.

Table 4.4: Layer thicknesses and expected Coefficients of Variance (in brackets) for three pavement structures analysed in this thesis (from TRH4 (1996) and Jooste (1998)).

Layer	National road structure	Provincial road structure	Rural road structure
Surfacing	50 mm Asphalt (7,5 mm)	Double seal (3 mm)	Double seal (3 mm)
Base	150 mm G1 (22,5 mm)	125 mm C3 (18,5 mm)	125 mm G4 (18,5 mm)
Subbase	300 mm C3 (45 mm)	152 mm C4 (30 mm)	125 mm G6 (18,5 mm)
Subgrade	500 mm SG1 (75 mm)	500 mm SG1 (75 mm)	500 mm SG1 (75 mm)

The material types included in the three typical pavement structures are a thin asphalt, double seal, crushed stone (G1), lightly cemented material (C3 and C4), natural gravel (G6) and selected subgrade (SG1) (all material codes according to TRH14 (1985)) (Table 4.4).

Engineering properties of materials were obtained from laboratory tests on the materials. These values were compared to typical published values to ensure that valid data were used. The specific engineering properties used in this thesis and their respective symbols are shown in Table 4.5.

Table 4.5: Engineering properties of the materials required in this thesis.

PROPERTY	SYMBOL	DATA
50 mm Asphalt		
Elastic modulus [MPa]	E	2 980
Shear modulus [MPa]	G	1 545
Poisson's Ratio	v	0,12
Damping coefficient	d	0,22
Mass density [kg/m^3]	ρ	2 300
Double seal		
The double seal does not posses any structural properties. Where needed in the finite element analyses similar properties as the 50 mm Asphalt is used.		
Crushed stone (G1)		
Elastic modulus [MPa]	E	420
Shear modulus [MPa]	G	210
Poisson's Ratio	v	0,20
Damping coefficient	d	0,10
Mass density [kg/m^3]	ρ	2 600
Natural Gravel (G4)		
Elastic modulus [MPa]	E	700
Shear modulus [MPa]	G	400
Poisson's Ratio	v	0,25
Damping coefficient	d	0,13
Mass density [kg/m^3]	ρ	2 000
Lightly cemented gravel (C3)		
Elastic modulus [MPa] Cemented state / equivalent granular state	E	2 000 / 300
Shear modulus [MPa]	G	1 000
Poisson's Ratio	v	0,3
Damping coefficient	d	0,15
Mass density [kg/m^3]	ρ	2 000
Lightly cemented gravel (C4)		
Elastic modulus [MPa] Cemented state / equivalent granular state	E	2 000 / 300
Shear modulus [MPa]	G	1 000
Poisson's Ratio	v	0,3
Damping coefficient	d	0,15
Mass density [kg/m^3]	ρ	2 000
Natural gravel (G6)		
Elastic modulus [MPa]	E	400
Shear modulus [MPa]	G	340
Poisson's Ratio	v	0,23
Damping coefficient	d	0,13
Mass density [kg/m^3]	ρ	1 980
Selected subbase (SG1)		
Elastic modulus [MPa]	E	100
Shear modulus [MPa]	G	42
Poisson's Ratio	v	0,48
Damping coefficient	d	0,24
Mass density [kg/m^3]	ρ	2 175

4.7 Observations

The following observations are made based on the information in this chapter:

a. The vehicle-pavement interaction process can be classified into various components that interact with each other in specific manners;
b. Ideal vehicle-pavement interaction analyses should cater for Basic, Intermediate and Advanced analysis levels, to fulfil different objectives, and
c. The differences in Displacement Power Spectral Density (DPSD) for different pavement profiles diminish at high spatial frequencies.

4.8 Conclusions

The following conclusions are made based on the information in this chapter:

a. All tyre loading can be classified as Static, Moving Static, Dynamic or Moving Dynamic Loading;
b. All pavement responses to tyre loading can be classified as either Static or Transient Response;
c. A vehicle-pavement interaction analysis should preferably be performed over compatible technology levels to obtain optimum benefit, and
d. Displacement Power Spectral Densities can be used to classify pavement profiles.

4.9 Recommendations

The recommendations provided in this chapter are mainly based on the assumptions, and thus highlights issues that are perceived to possibly affect vehicle-pavement interaction, but which fall outside the scope of this thesis.

The following recommendations are made:

a. It is recommended that the effect of variations in vehicle component characteristics on pavement response analysis be investigated, after the need for dynamic vehicle-pavement interactions are established;
b. It is recommended that a study into the effects of travel around corners and the effect of parameters such as radius and camber of the corner on pavement response analysis be performed;
c. It is recommended that the effect of variations in pavement characteristics on pavement response analysis be performed;
d. It is recommended that an investigation regarding transfer functions for moving dynamic loads on South African pavements be performed upon successful indication that the effect of dynamic loads and pavement response is of such a nature that these types of analyses should be performed as routine;

e. It is recommended that further work be conducted into tyre loads where payloads which are not evenly distributed over the available axles (leading to some axles being loaded higher than others) are used in the vehicle simulations;

f. It is recommended that detailed studies incorporating specific data (overloaded extent and degree) for various regions into dynamic vehicle-pavement interaction be performed once the basic techniques are developed, and

g. It is recommended that the effects of non-linear material characteristics on vehicle-pavement interaction be investigated in detail.

4.10 References

COLLOP, A.C. and CEBON, D. 1995a. **Parametric study of factors affecting flexible-pavement performance.** Journal of Transportation Engineering, Volume 121, Number 6, pp 485-494.

COLLOP, A. and CEBON, D. 1995b. **Modelling whole-life pavement performance.** In: Road Transport Technology 4; edited by C.B. Winkler. (Proceedings of the fourth international symposium on heavy vehicles and dimensions, held in Ann Arbor, MI, 25-29 June 1995). Ann Arbor, MI: University of Michigan Transportation Research Institute.

DIVINE see Dynamic Interaction of Vehicle & Infrastructure Experiment.

Dynamic Interaction of Vehicle & Infrastructure Experiment: Asia-Pacific Concluding Conference. 1997. Melbourne, Australia: ARRB-TR.

DIMAROGONAS, A. 1996. **Vibration for Engineers.** New Jersey: Prentice-Hall Inc.

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

Guidelines for road construction materials. 1985. Pretoria: Committee of Land Transport Officials (COLTO), Department of Transport. (Technical Recommendations for Highways; TRH14).

HAAS, R., HUDSON, W.R. and ZANIEWSKI, J. 1994. **Modern pavement management.** Malabar, Florida: Krieger Publishing Company.

HORAK, E., KLEYN, E.G., DU PLESSIS, J.A., DE VILLIERS, E.M. and THOMPSON, A.L. 1992. **The impact and management of the Heavy Vehicle Simulator (HVS) fleet in South Africa.** Proceedings of the 7th International Conference on Asphalt Pavements, Nottingham, UK.

HRB, 1962. **The AASHO road test.** Highway Research Board, Special Report 73, Washington, DC, USA.

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

JOOSTE, F.J. 1997. **Probabilistic pavement analysis and design.** Pretoria: Division for Roads and Transport Technology, CSIR (Technical Report TR-97/035).

KANNEMEYER, L. 1998. **Personal communication on National Roads Agency Pavement Management System Database.** Pretoria: South African National Roads Agency Ltd.

KEMP, M. 1999. **Personal communication on surface roughness data in HSP database.** Pretoria: CSIR, Project leader.

NORDENGEN, P. 1999. **Personal communication on overloading statistics for heavy vehicles in South Africa.** Pretoria: Division for Roads and Transport Technology, Project Manager.

Structural design of flexible pavements for interurban and rural roads. 1996. Pretoria: Committee of Land Transport Officials (COLTO), Department of Transport. (Technical Recommendations for Highways; TRH4).

THEYSE, H.L., DE BEER, M., and RUST, F.C. 1996. **Overview of the South African Mechanistic Design Method.** Paper presented at the 75th annual Transportation Research Board meeting, Washington.

TRH 4 see Structural design of flexible pavements for interurban and rural roads.

TRH 14 see Guidelines for road construction materials.

ULLIDTZ, P. 1987. **Pavement analysis.** Lyngby, Denmark: Institute of Roads, Transport and Town Planning. (Developments in Civil Engineering Vol. 19).

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.

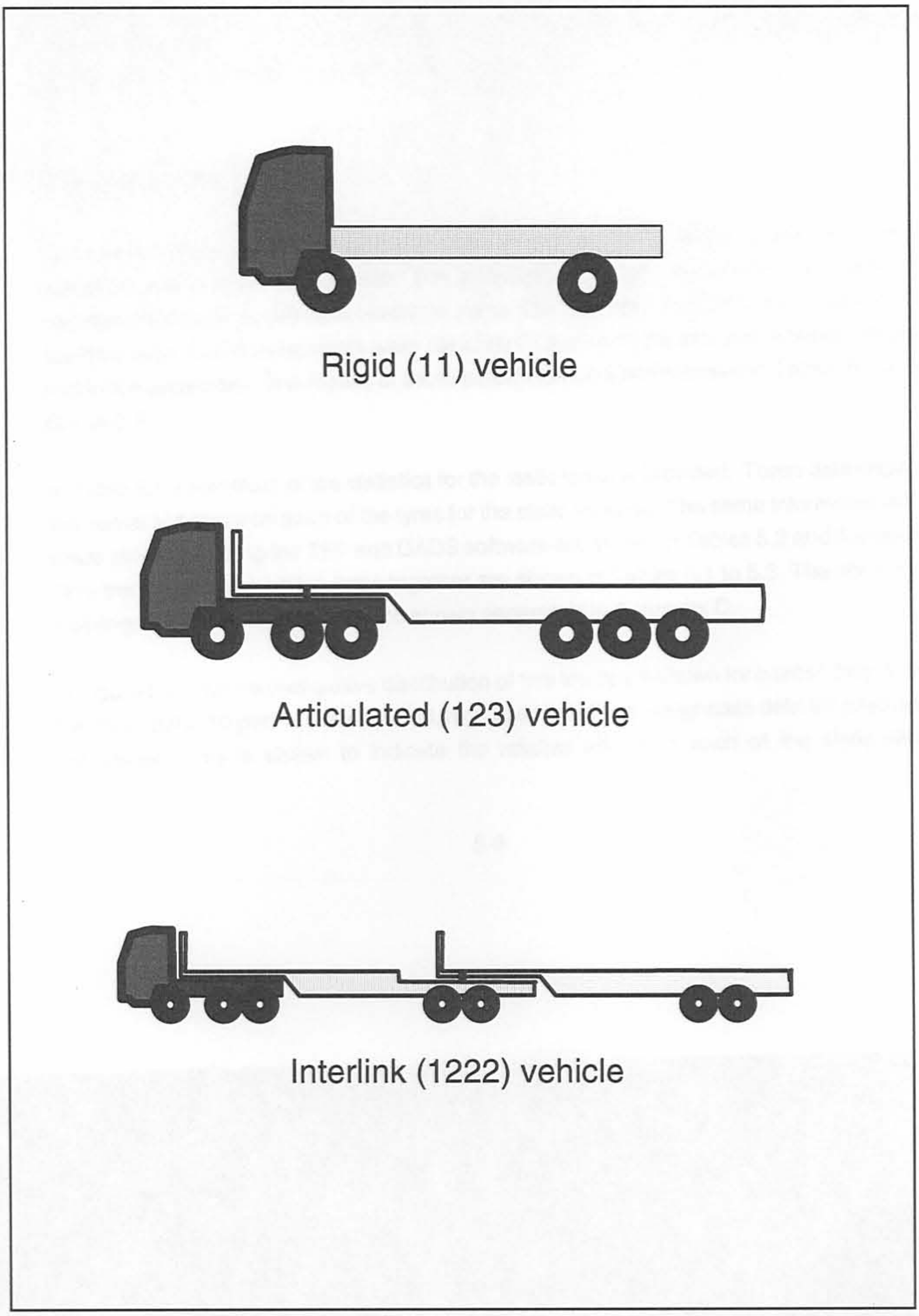


Figure 5.1: **Schematic of 3 vehicles used in tyre load simulations.**

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	Not applicable due to static loads			Not applicable due to static loads		
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						
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 mil3	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

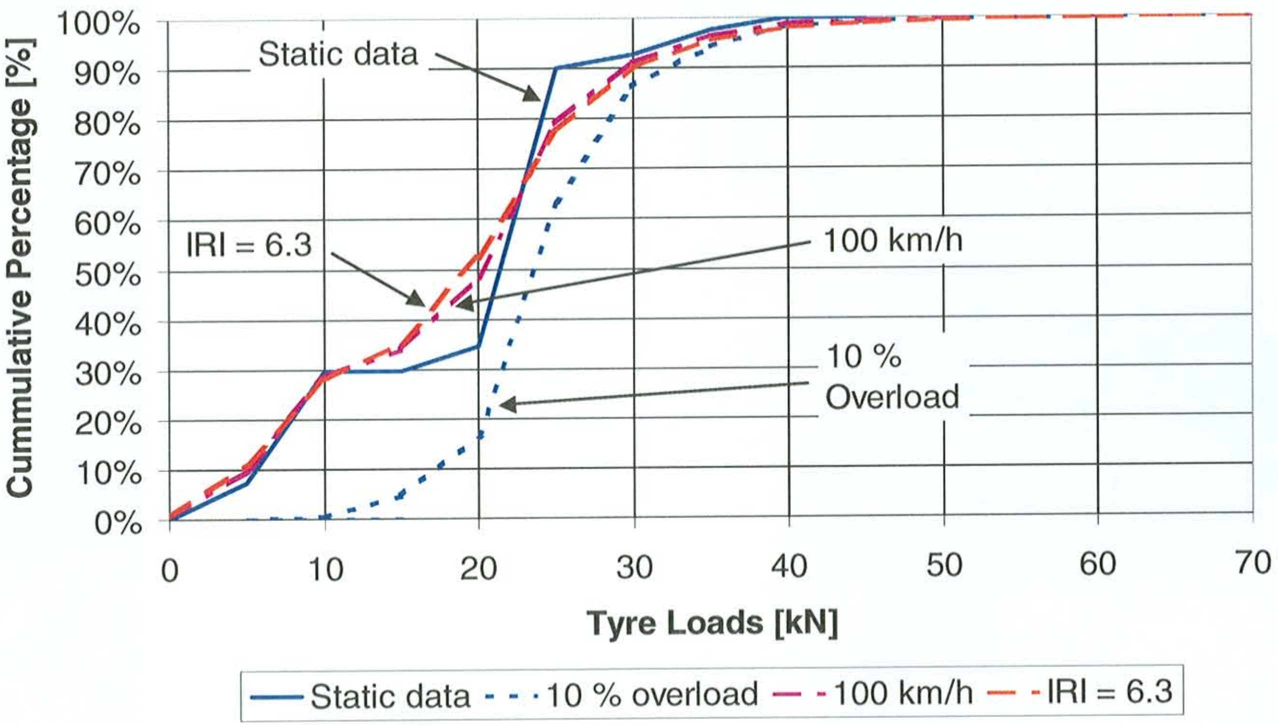


Figure 5.2: **Cumulative distribution of tyre loads of all vehicles as simulated using DADS software.**

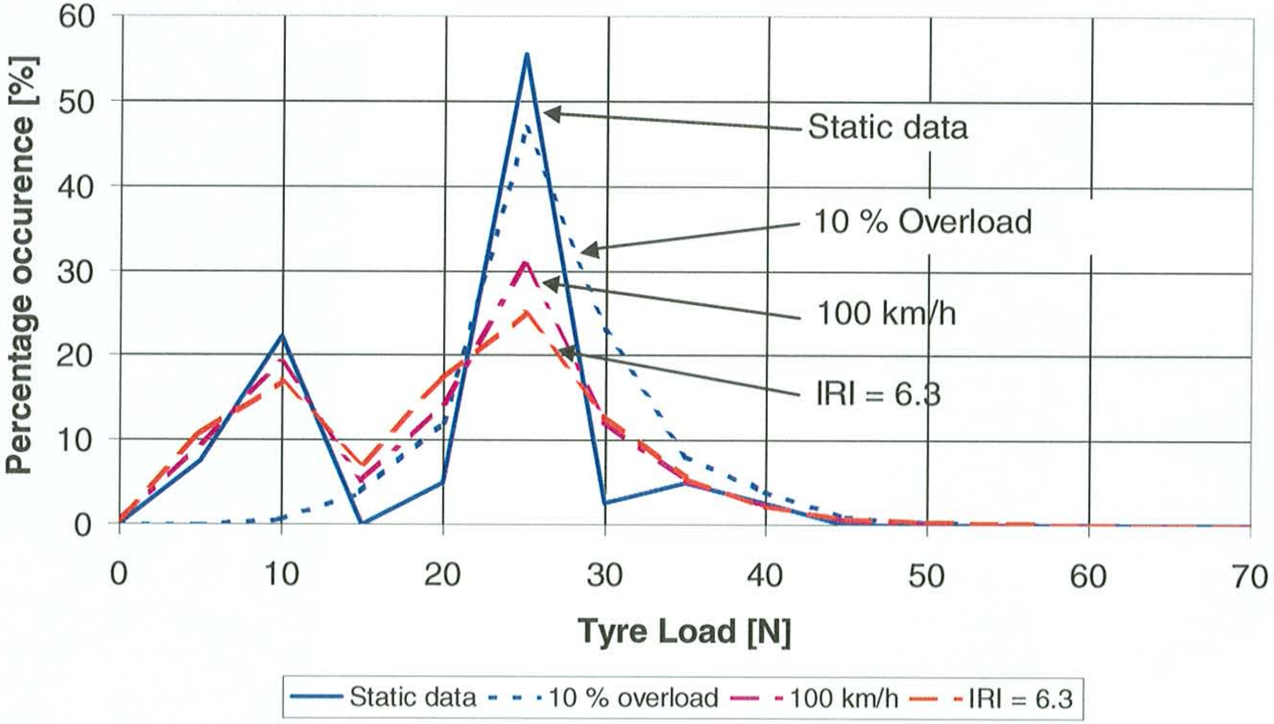


Figure 5.3: Histogram of tyre loads of all vehicles as simulated using DADS software.

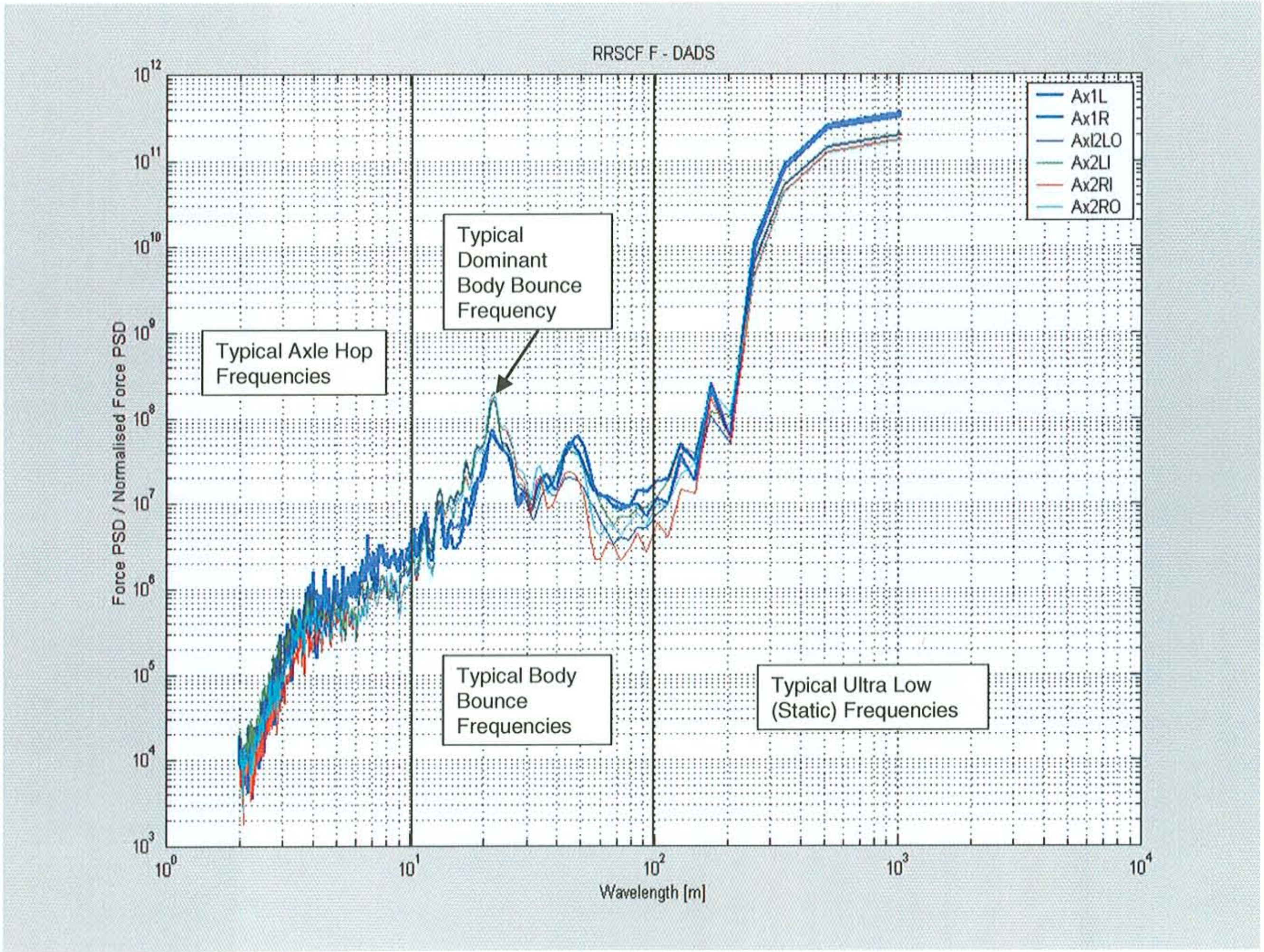


Figure 5.4: **Typical Power Spectral Density (PSD) plot for tyre loads, indicating typical axle hop, body bounce and ultra low frequencies.**

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.

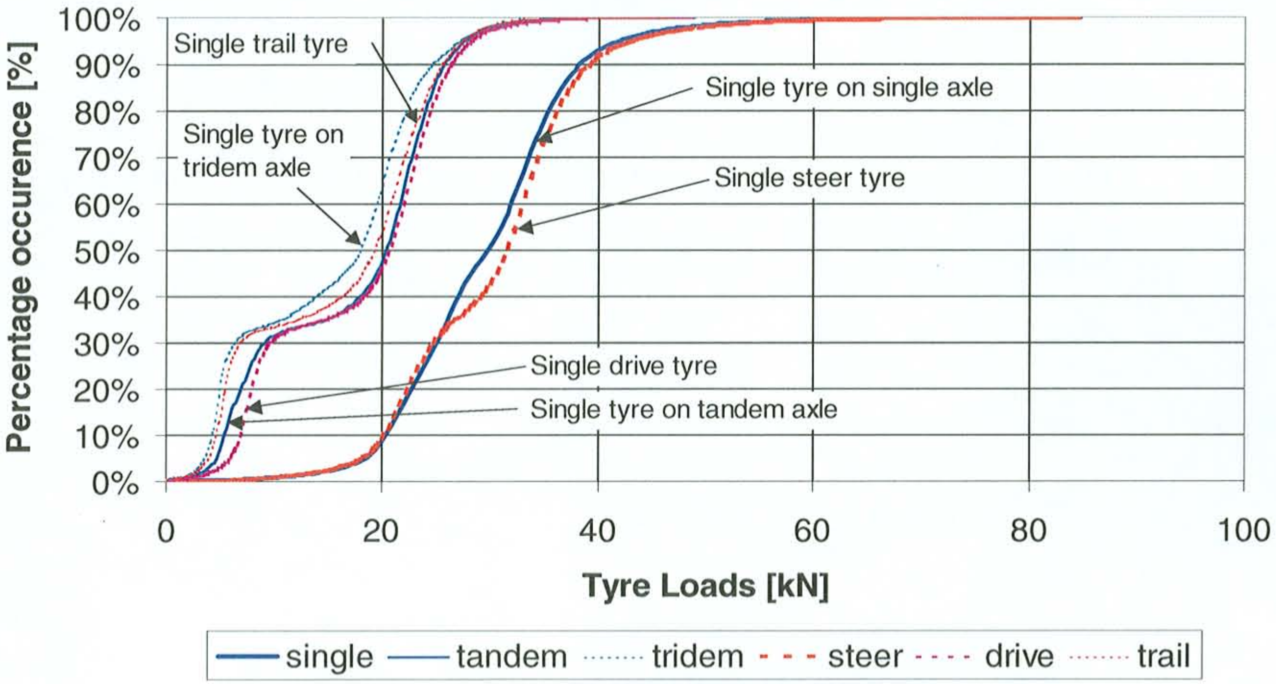


Figure 5.5: Relationship between single, tandem and tridem and steer, drive and trail axles for all vehicles and conditions simulated (DADS simulated data).

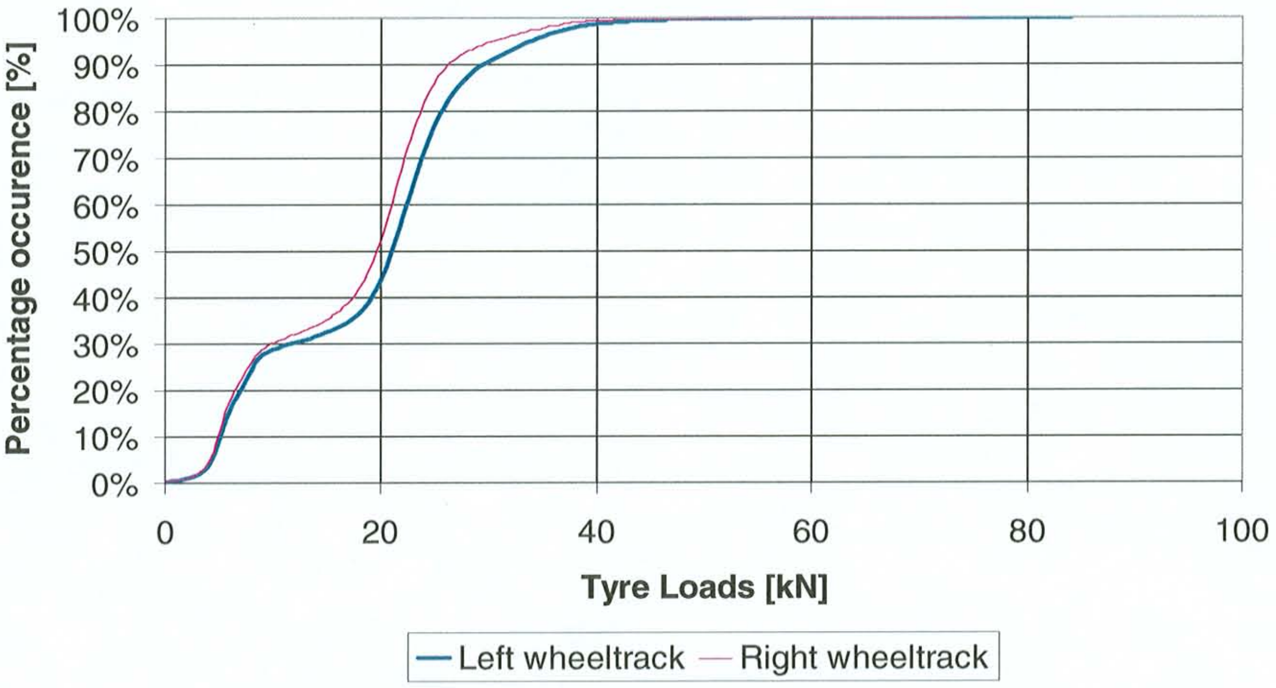


Figure 5.6: **Comparison between left and right wheeltrack tyre load data for all vehicles and conditions simulated (DADS simulated data).**

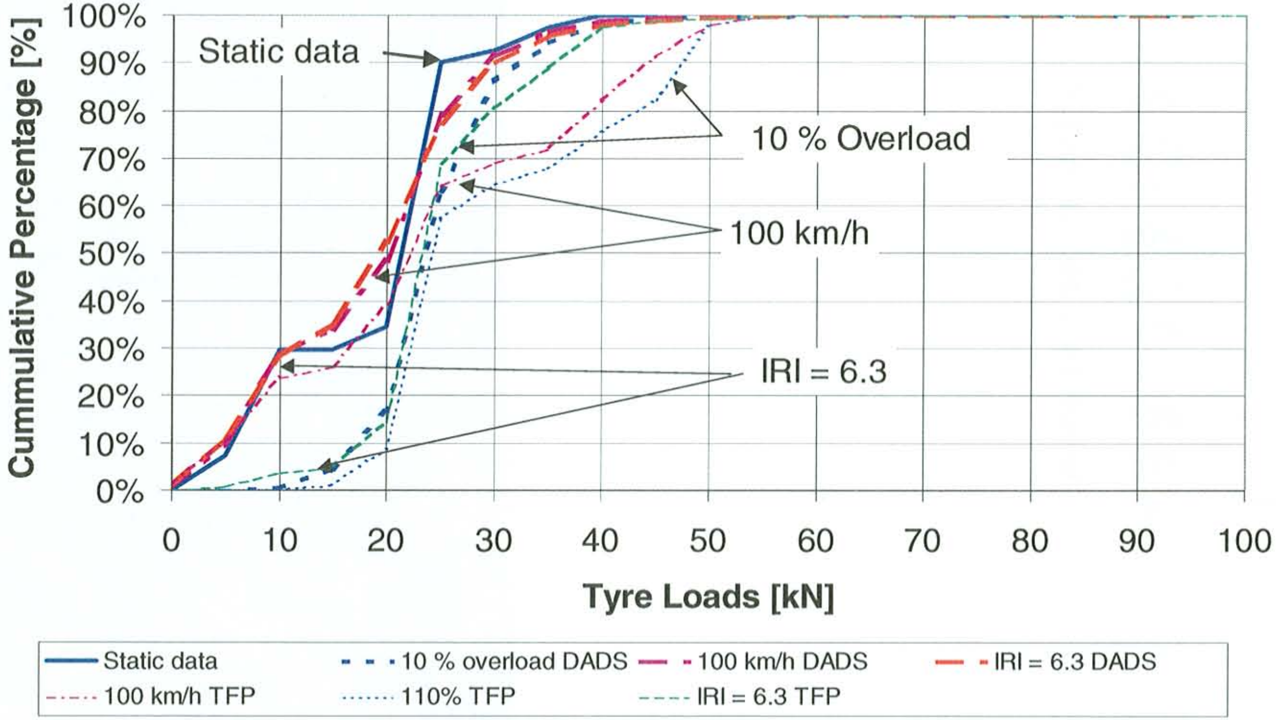


Figure 5.7: **Comparison of data obtained from static and DADS and TFP simulations for all vehicles and indicated conditions.**

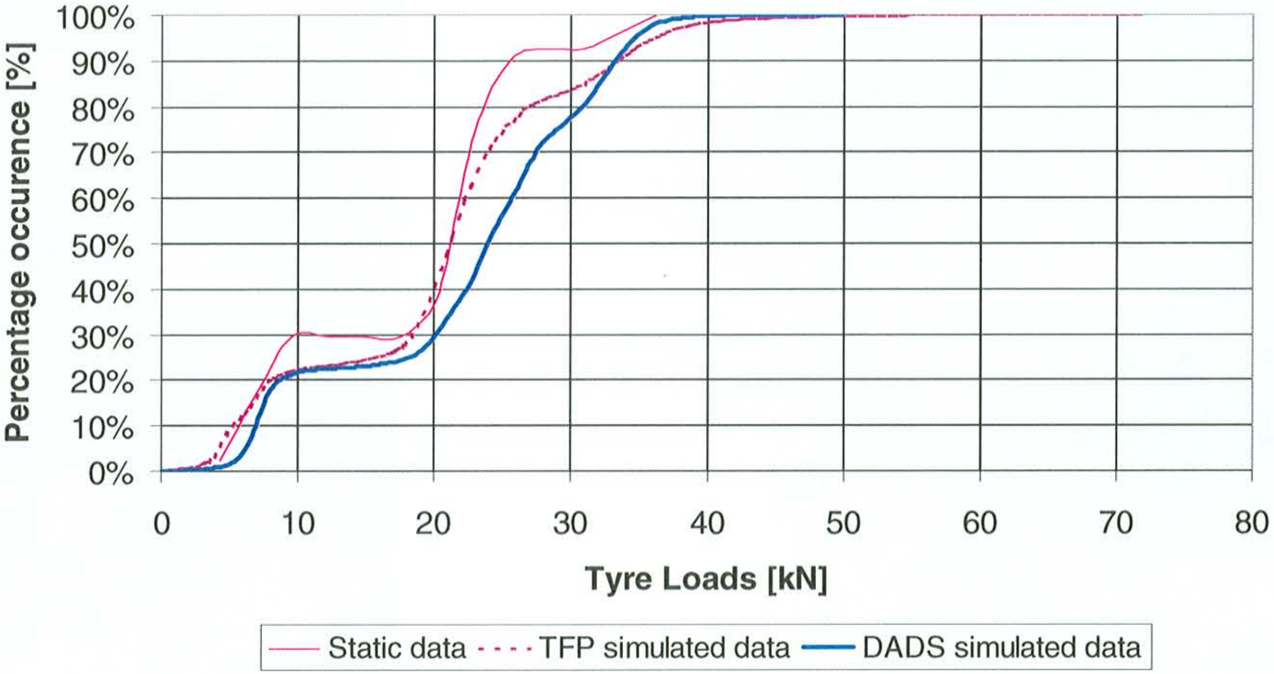


Figure 5.8: **Relationship between static, TFP and DADS data for all vehicles and conditions simulated.**

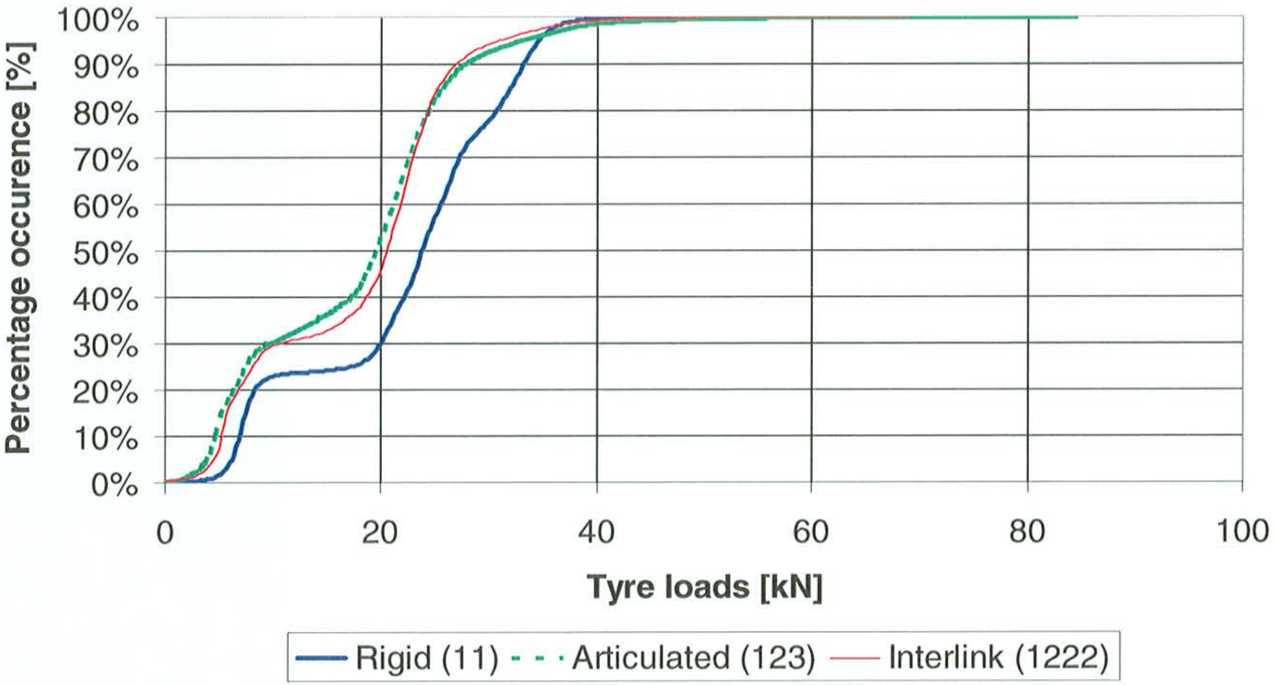


Figure 5.9: Cumulative distributions of tyre loads for Rigid (11), Articulated (123) and Interlink (1222) vehicles.

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).

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

Average Load [N]
GVM [N]
$R^2 = 99{,}9\ \%$
Correlation Coefficient = 0,999
Standard error of y – estimate = 97,1

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

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

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.

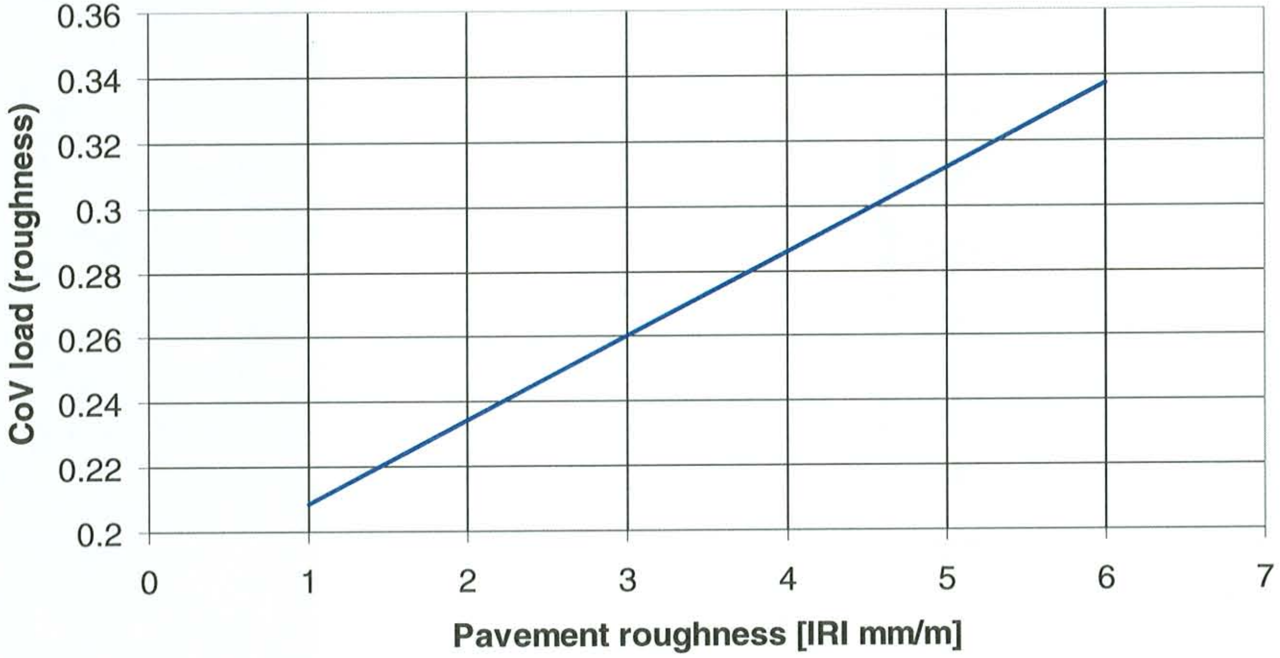


Figure 5.10: Effect of pavement roughness on Coefficient of Variation (CoV) in tyre load (based on Equations 5-1 and 5-2).

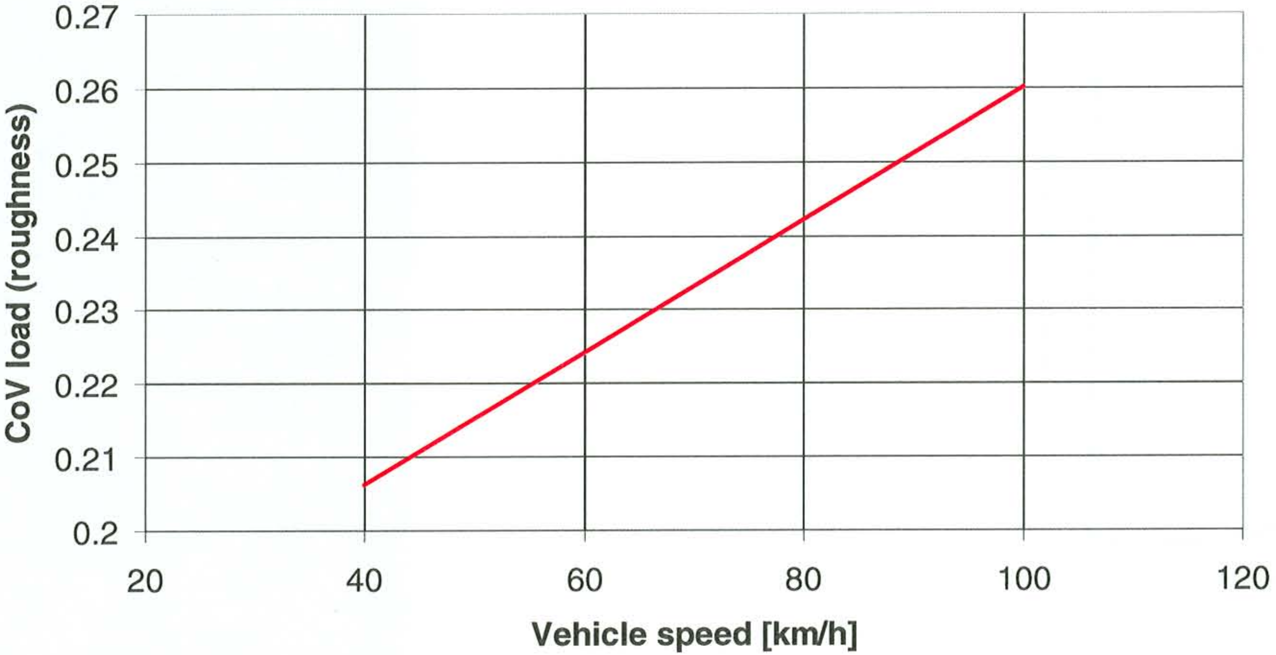


Figure 5.11: Effect of vehicle speed on Coefficient of Variation (CoV) in tyre load (based on Equations 5-1 and 5-2).

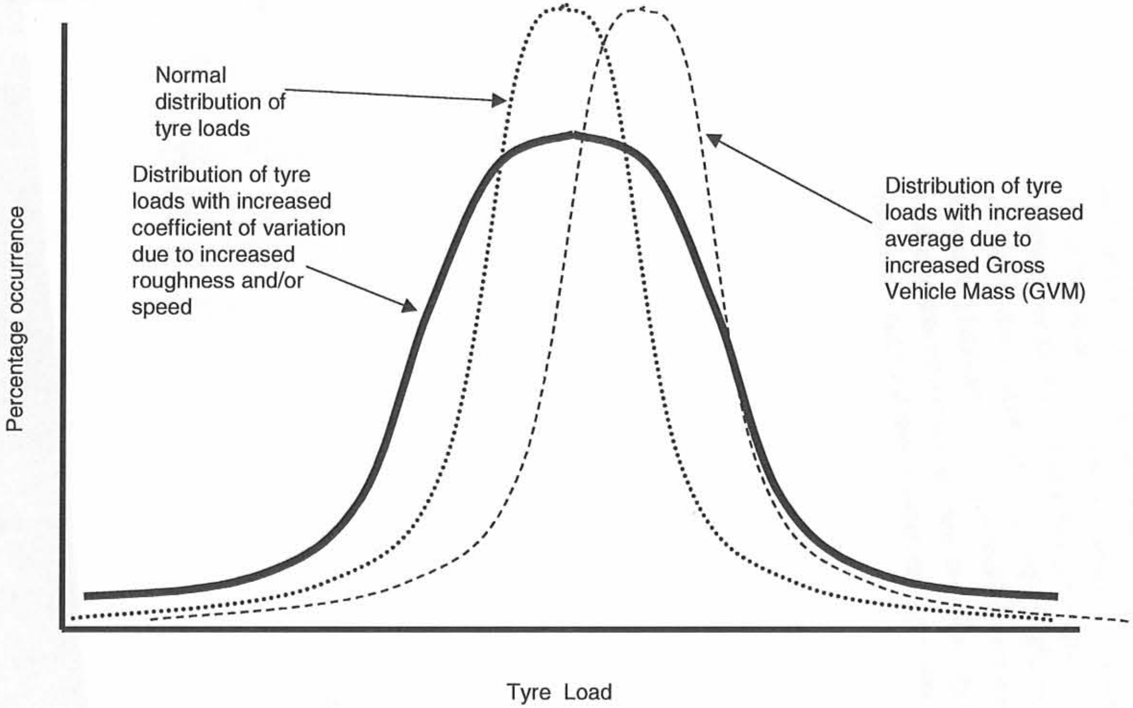


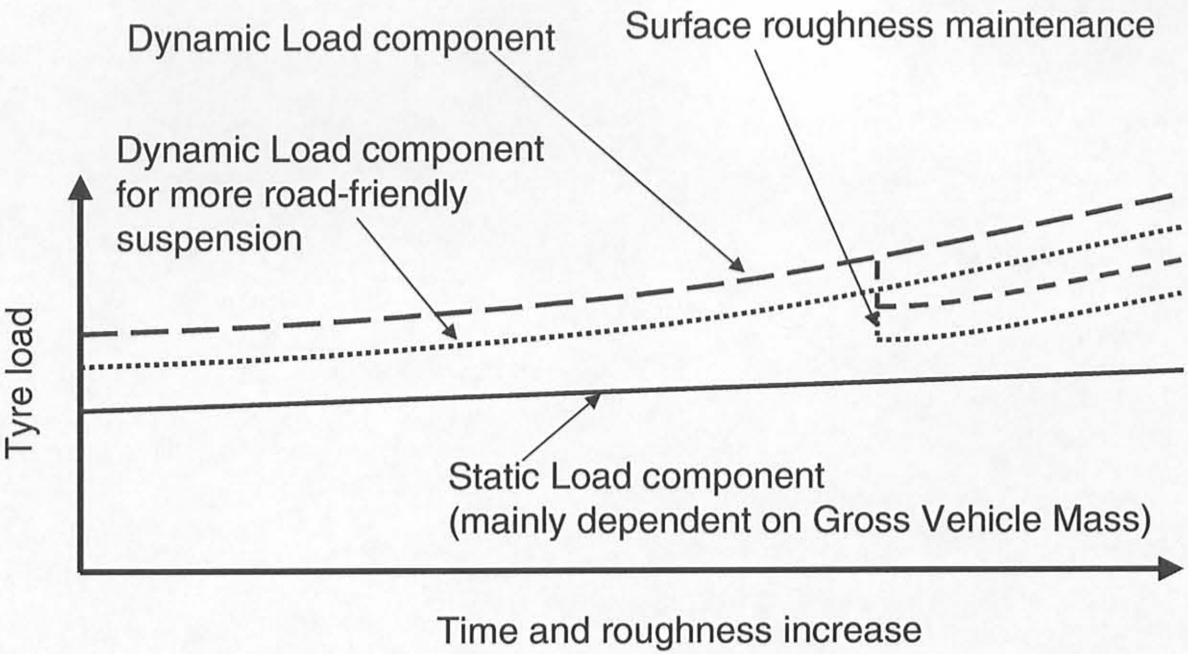
Figure 5.12: **Schematic of changes in average and standard deviation of tyre loads.**

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).

$$\begin{aligned}
&\text{Lowfrequency} = -2{,}1\text{E}7 + 1{,}5 * \text{GVM} * \text{roughness} * \text{speed}\\
&\quad \text{Lowfrequency [Nm]}\\
&\quad \text{GVM [N]}\\
&\quad \text{roughness [HRI]}\\
&\quad \text{speed [km/h]}\\
&\quad R^2 = 76.6\ \%\\
&\quad \text{Correlation Coefficient} = 0{,}88\\
&\quad \text{Standard error of y} - \text{estimate} = 6{,}1\text{E}7
\end{aligned}$$

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

$$\begin{aligned}
&\text{Dynamic component} = (1\ 072 + 1{,}3 * \text{roughness} * \text{speed} * \text{number of tyres})^2\\
&\quad \text{Dynamic component [Nm]}\\
&\quad \text{roughness [m/m]}\\
&\quad \text{speed [km/h]}\\
&\quad R^2 = 81{,}9\ \%\\
&\quad \text{Correlation Coefficient} = 0{,}91\\
&\quad \text{Standard error of y} - \text{estimate} = 2\ 082{,}78
\end{aligned}$$

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.

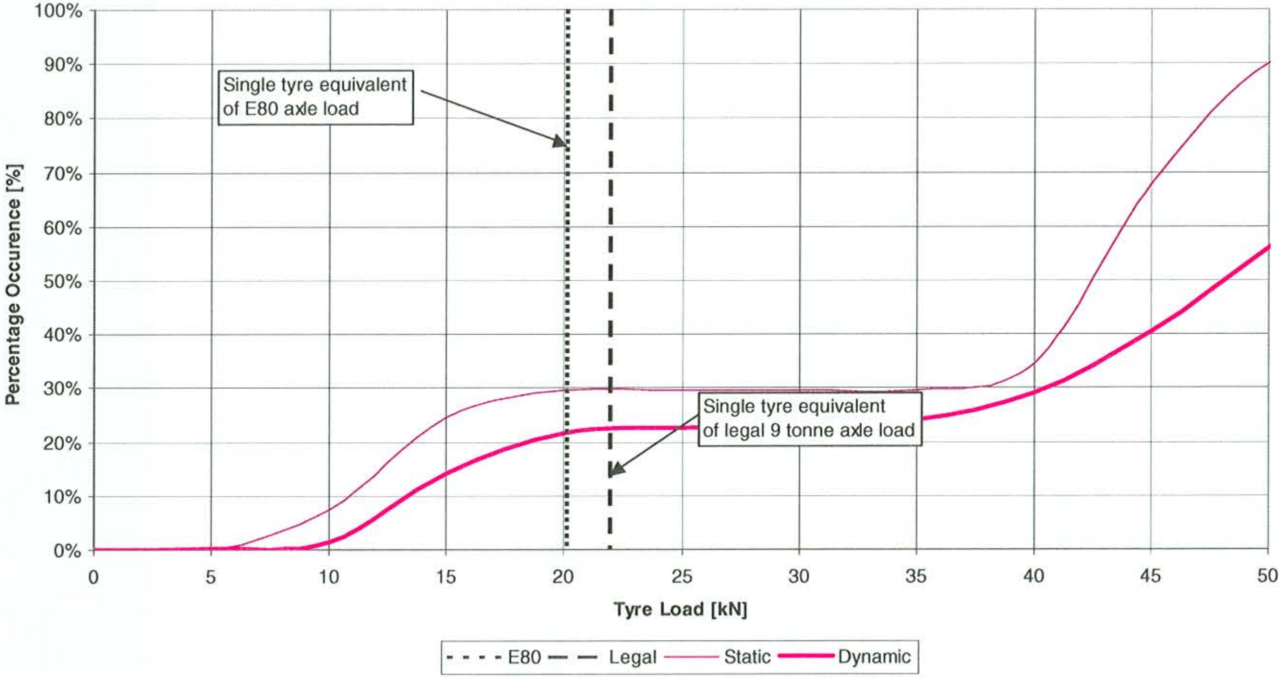


Figure 5.14: Cumulative distribution of DADS-generated dynamic tyre loads and Static tyre loads from which the tyre loads for pavement response analysis in Tables 5.5 and 5.6 were selected, showing the relation to the E80 and legal tyre loads (data shown are for all vehicles and conditions simulated).

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

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).

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

Structural design of flexible pavements for Interurban and rural roads. 1996. Pretoria: Committee of Land Transport Officials (COLTO). Department of Transport (DOT), (DOT Technical Recommendations for Highways; Draft TRH4).

SWEATMAN, P.F. 1983. **A study of dynamic wheel forces in axle group suspensions of heavy vehicles.** Victoria: Australian Road Research Board. (Special Report 27).

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

6. PAVEMENT RESPONSE

6.1. Introduction

The third major topic of this thesis is pavement response, and in particular transient response of pavement structures to moving loads. In Section 2.5 a number of issues around pavement structure response were identified. The purpose of Section 2.5 was mainly to determine the current best available knowledge and the current needs for developments and improvements.

The objective of this chapter is to evaluate two pavement response procedures and indicate the nominal differences between static and transient pavement response parameters. Transient response is defined as the response of a pavement to a moving load input. The effects of vehicle speed, pavement mass inertia and damping on pavement response are included in a transient analysis.

The focus in this chapter is on the response of three specific pavement structures to the tyre loads developed in Chapter 5. Only linear elastic material models are used for the response analyses, and existing transfer functions from the South African Mechanistic Design Method (SAMDM) (Theyse et al, 1996) are used to evaluate the expected lives calculated from the different analysis methods. Development of improved material models and transfer functions are explicitly excluded from this thesis (see Section 4.5.3).

Although there are only three basic pavement structures used for the analyses in this thesis (refer to Table 2.8 and Sections 2.6.3 and 4.6.2), two of these pavement structures (the national and provincial pavements) incorporate lightly cemented layers in their structures. These materials change to an equivalent granular state relatively early in their lives. This changes the properties of the materials. To calculate realistic pavement responses and lives, these two pavement structures are evaluated in both a cemented (suffix ***cem***) and equivalent granular (suffix ***eg***) state in this chapter. This cause the analyses to be performed on five pavement structures, although the pavement lives are combined in the end to provide only a pavement life for each of the three nominal pavement structures. To expedite analyses and contain the amount of data for analysis, only the first (fully cemented) and the final (fully equivalent granular state) phases of the provincial pavement's life were analysed.

The chapter is structured into a static response analysis and a transient response analysis. In each of these sections the primary results of the specific analysis are discussed together with inferences based on the specific data. In Section 6.4 the data from the analyses are compared. In Section 6.5 a method is developed for converting between static and moving pavement response parameters.

6.2. Static Response Analysis

6.2.1. Introduction

Static linear elastic pavement structure response analysis is defined, for the purposes of this thesis, as the calculation of stresses, strains and deflections in a pavement, caused by a time-independent tyre load that is fixed at one location. The stresses, strains and deflections are related to the applied tyre load through a linear elastic material model. This type of analysis is termed static response analysis in the remainder of this thesis.

The objective of this section is to obtain the pavement responses and expected lives that would normally be obtained using the procedures typically used in South Africa. The loads used consist of static loads distributed over circular areas of uniform contact stresses. The pavement structure is defined in terms of layer thicknesses, material stiffnesses and Poisson ratios. The pavement response is converted to expected pavement lives using the SAMDM transfer functions (Theyse et al, 1996).

The tyre loads used originate from the tyre load distribution obtained from evaluating all the static tyre loads of all three the vehicles at the three load conditions defined in Chapter 5. The specific loads are shown in Tables 5.5 and 6.1. Tyre loads at the 50th, 80th, 90th and 95th percentile values are used as input data. The correspondent axle load (assuming a single axle with dual tyres) and equivalent 80 kN load (assuming an exponent of 4,0) for each of the load cases are also shown in Table 6.1. The pavement structures for which the analyses were performed are shown in Tables 4.4 and 6.2. The material properties used for each of the layers are shown in Table 4.5.

Table 6.1: **Selected tyre loads (single tyre) for static 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

Table 6.2: **Layer thicknesses for three pavement structures analysed in this thesis (from TRH4 (1996).**

Layer	National road structure	Provincial road structure	Rural road structure
Surfacing	50 mm Asphalt	Double seal	Double seal
Base	150 mm G1	125 mm C3	125 mm G4
Subbase	300 mm C3	152 mm C4	125 mm G6
Subgrade	500 mm SG1	500 mm SG1	500 mm SG1

The stress, strain and deflection responses from the pavement structures were evaluated using the ELSYM5M (ELSYM5M, 1995) and SAMDM (Theyse and Muthen, 2000) software. Both these methods use the ELSYM engine, but the SAMDM procedure also calculates the expected lives of the various layers and the pavement structure.

The load case used for all the analyses consisted of a single tyre load applied to the pavement structure. This was done to enable direct comparison with the responses calculated using the axi-symmetric finite element software (Section 6.3). In the remainder of this section the pavement responses calculated and expected lives for each of the pavement structures and load cases are discussed. These results are compared to those obtained from the other analysis method in Section 6.4.

6.2.2. Pavement response from static response analysis

The data obtained from the static response analyses consist of stresses, strains and deflections at various locations in the pavement structure. These locations were based on the critical positions in the pavement structure for each parameter.

The deflection responses were calculated on the surface of the pavement structure, at distances from the centre of the tyre load shown in Table 6.3. The stress and strain responses were calculated at the centre of the tyre load at depths indicated in Table 6.4. These distances and depths coincided with the layer interfaces and the mesh selected for the axi-symmetric finite element analyses. The shear stresses and strains were calculated under the edge of the tyre. The maximum pavement response values for the static response analyses are shown in Table 6.5.

Table 6.3: Positions at which elastic surface deflections were calculated for each pavement structure.

	National road structure	Provincial road structure	Rural road structure
Distance from centre of tyre load [mm]	0 mm	0 mm	
	102 mm	102 mm	
	305 mm	279 mm	
	762 mm	787 mm	
	2 921 mm	2 057 mm	

Table 6.4: Depths at which stresses and strains were calculated for each pavement structure.

	National road structure	Provincial road structure	Rural road structure
Depth below centre of tyre load [mm]	0 mm	0 mm	0 mm
	51 mm	76 mm	63 mm
	127 mm	127 mm	127 mm
	203 mm	203 mm	190 mm
	508 mm	279 mm	250 mm

Table 6.5: Maximum stresses, strains and deflections calculated for each pavement structure.

Parameter	National road structure[1]	Provincial road structure[1]	Rural road structure
Maximum elastic surface deflection [mm]	0,32 (0,41) surface	0,28 (0,79) surface	0,57 surface
Vertical compressive strain [με]	948 (897) centre G1	2 058 (268) centre EG3	920 bottom G4
Horizontal tensile strain [με]	397 (421) bottom AC	141 bottom C4 (817) centre EG4	465 bottom G4
Vertical compressive stress [kPa]	1 069 (1 069) surface	1 069 (1 069) surface	1 069 surface
Horizontal compressive stress [kPa]	2 523 (2 978) surface	1 298 (1 104) surface	1 355 surface
Shear compressive stress [kPa]	55 (67) surface	148 (85) centre of C3/EG3	165 centre of G4

[1] Values for equivalent granular state shown in brackets.

Analysis of the results of the pavement structure response calculations indicated the following (all responses indicated below the centre of the loaded area except for the shear parameters which were located at the edge of the loaded area). These responses are as would be expected from existing pavement analysis knowledge, but are emphasised here to indicate that the analysis method and parameters caused responses normally expected from these conditions:

Elastic surface deflection

The trends observed in the data for each pavement structure (regardless of applied load percentile) were similar for the specific pavement. The higher percentile loads caused deeper deflections than the lower percentile loads. Typical elastic deflection bowls for each of the pavements at the 50th load percentile are shown in Figure 6.1. The rural, national ***eg*** and provincial ***eg*** structures had higher elastic deflections close to the loaded areas than the national ***cem*** and provincial ***cem*** pavement structures. This may be attributed to the high stiffness cemented layers (national ***cem*** and provincial ***cem*** pavements) as well as the high stiffness asphalt surfacing (national pavement). Similar deflection values were calculated further than 500 mm from the centre of the load for all pavement structures. These similar deflections were caused by the same subgrade used for all the pavement structures in the analyses.

Vertical elastic strain

Similar trends were observed in the vertical strains calculated for each pavement structure, regardless of applied load percentile. Typical vertical strains for each of the pavement structures are shown in Figure 6.2 at the 50th load percentile. Compressive strains were calculated at all depths except the surface. The tensile surface strains calculated on the surface is probably due to a modelling effect, and is generally found for these types of analyses. The provincial ***eg*** pavement yielded a compressive vertical strain on the surface as well as the highest overall strain value. The provincial pavement ***cem*** yielded the lowest vertical strains due to the presence of two lightly cemented layers in the pavement structure. The major difference between the provincial pavement structure response in the cemented and the equivalent granular phases is the large difference in elastic modulus before and after cracking (decrease from 2 000 MPa to 400 MPa. The responses from the rural and national (***cem*** and ***eg***) pavements were similar, due to the presence of granular layers in both these pavements.

Horizontal elastic strain

Each of the pavement structures yielded similar trends for the calculated horizontal strains at the depths investigated at all load percentiles. The higher load percentiles yielded higher strains. Tensile strains were calculated at all depths except on the surface. Typical trends for each of the pavements are shown in Figure 6.3. The highest horizontal strains were calculated in the provincial ***eg*** pavement, with the provincial ***cem*** pavement exhibiting the lowest horizontal tensile strains. The horizontal strains were mainly influenced by the elastic stiffnesses of the materials.

Vertical stress

Vertical compressive stresses calculated for the various pavement structures showed similar trends for all the pavements at all load percentiles (Figure 6.4). The calculated stresses at the surface correlated exactly with the applied uniform contact stresses. Stresses decreased with depth in the pavement, and increased with increased load magnitudes.

Horizontal stress

The horizontal stresses calculated for the various pavement structures showed similar trends (Figure 6.5), except for the national (***cem*** and ***eg***) pavements. The rural and provincial pavements (***cem*** and ***eg***) showed tensile stresses at depths of deeper than 130 mm, while the national pavements (***cem*** and ***eg***) showed tensile stresses at a depth of 50 mm. Tensile stresses cannot be generated in granular layers. However, this is a phenomenon previously shown to occur when analysing a granular pavement using linear elastic theory (Theyse et al, 1996).

Shear stress

The shear stresses calculated for the rural and provincial (***cem*** and ***eg***) pavement structures showed similar trends (Figure 6.6). Higher shear stresses were calculated in the centre of the base layer, with lower stresses at deeper locations in the pavements. The national (***cem*** en ***eg***) pavements showed a different trend with a lack of the high shear stresses in the base layer. This may be attributed to the thicker and stiffer asphalt surfacing used for these pavements.

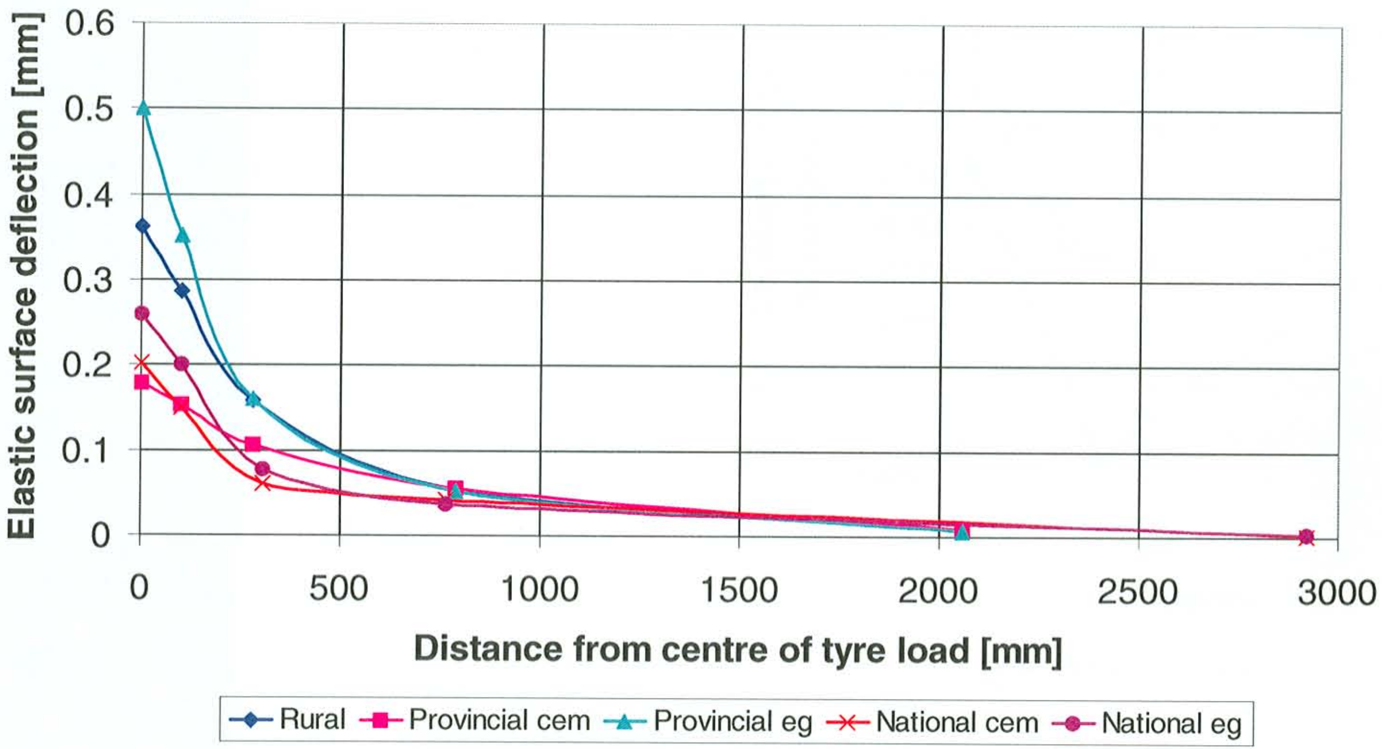


Figure 6.1: Typical elastic surface deflection data (under centre of load) for pavements evaluated using 50th percentile static load.

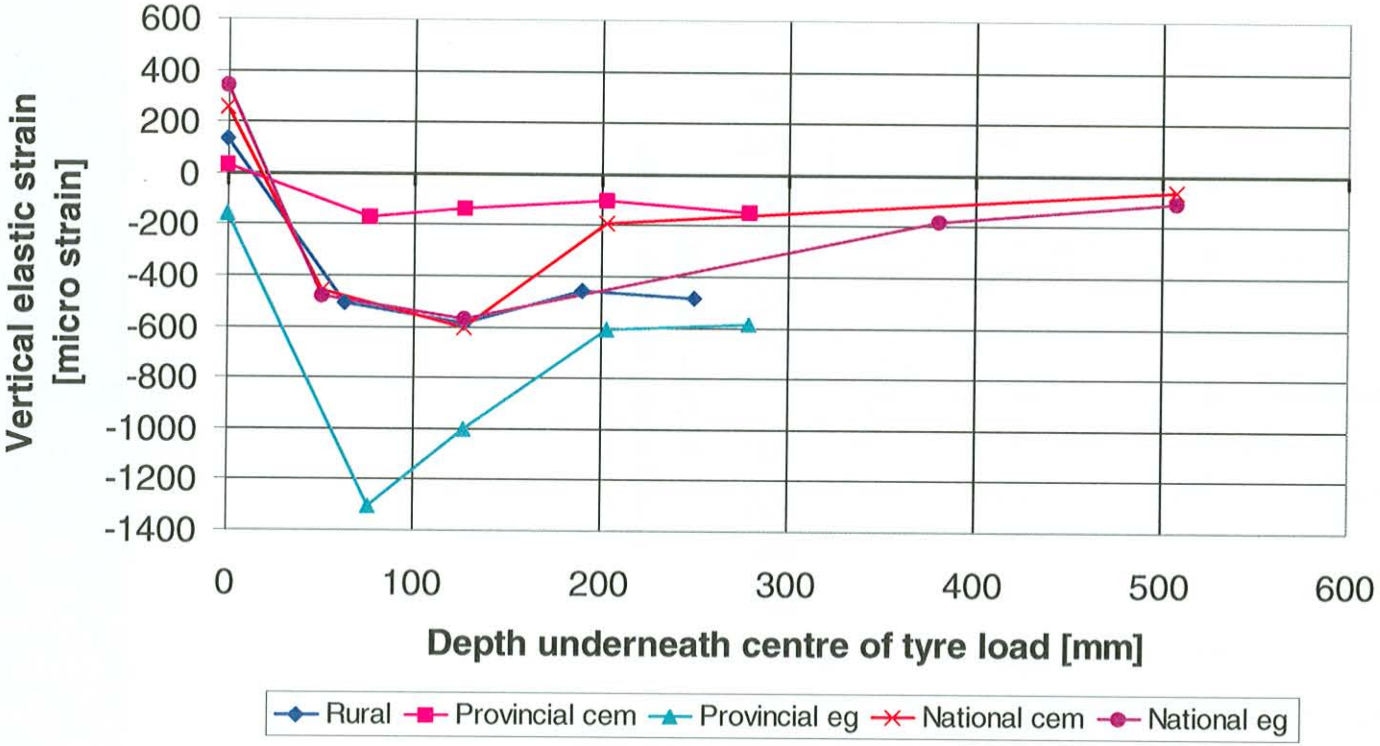


Figure 6.2: Typical vertical strain data (under centre of load) for pavements evaluated using 50th percentile static load.

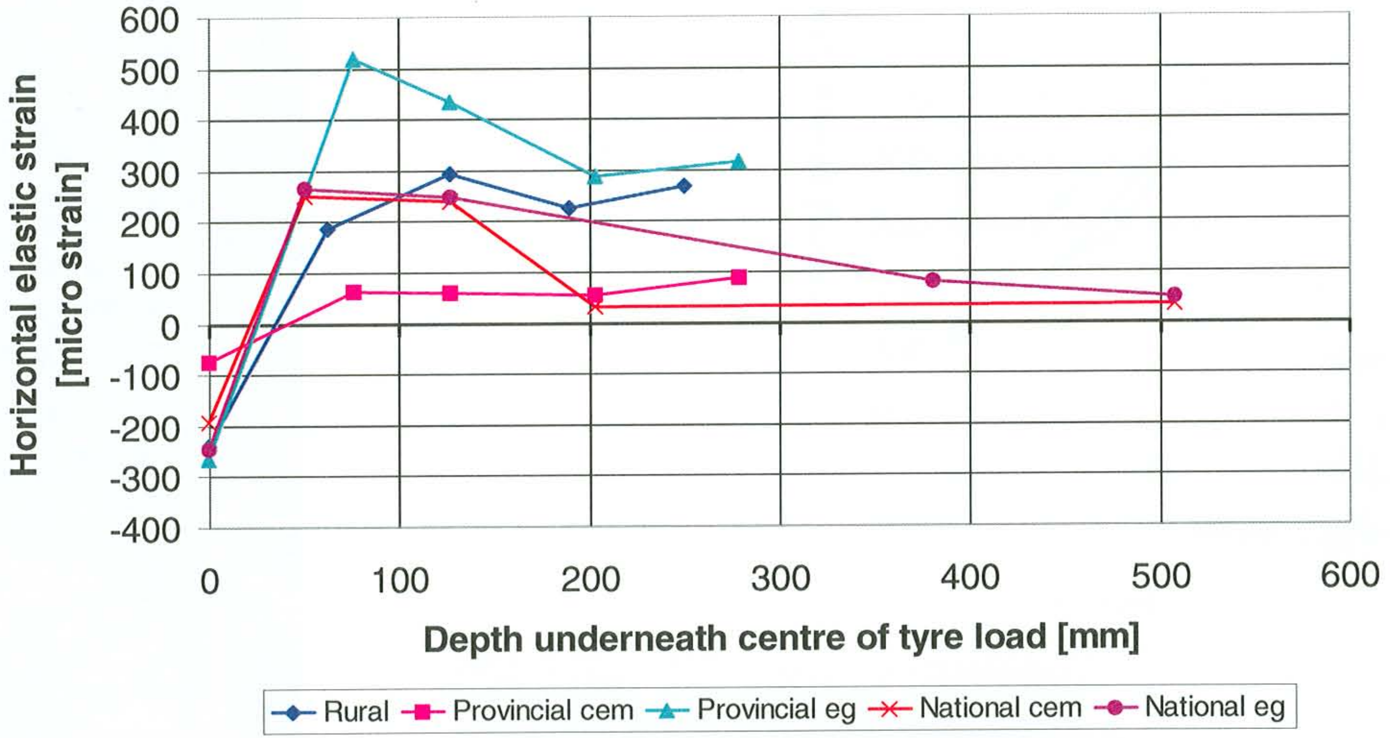


Figure 6.3: Typical horizontal tensile strain data (under centre of load) for pavements evaluated using 50th percentile static load.

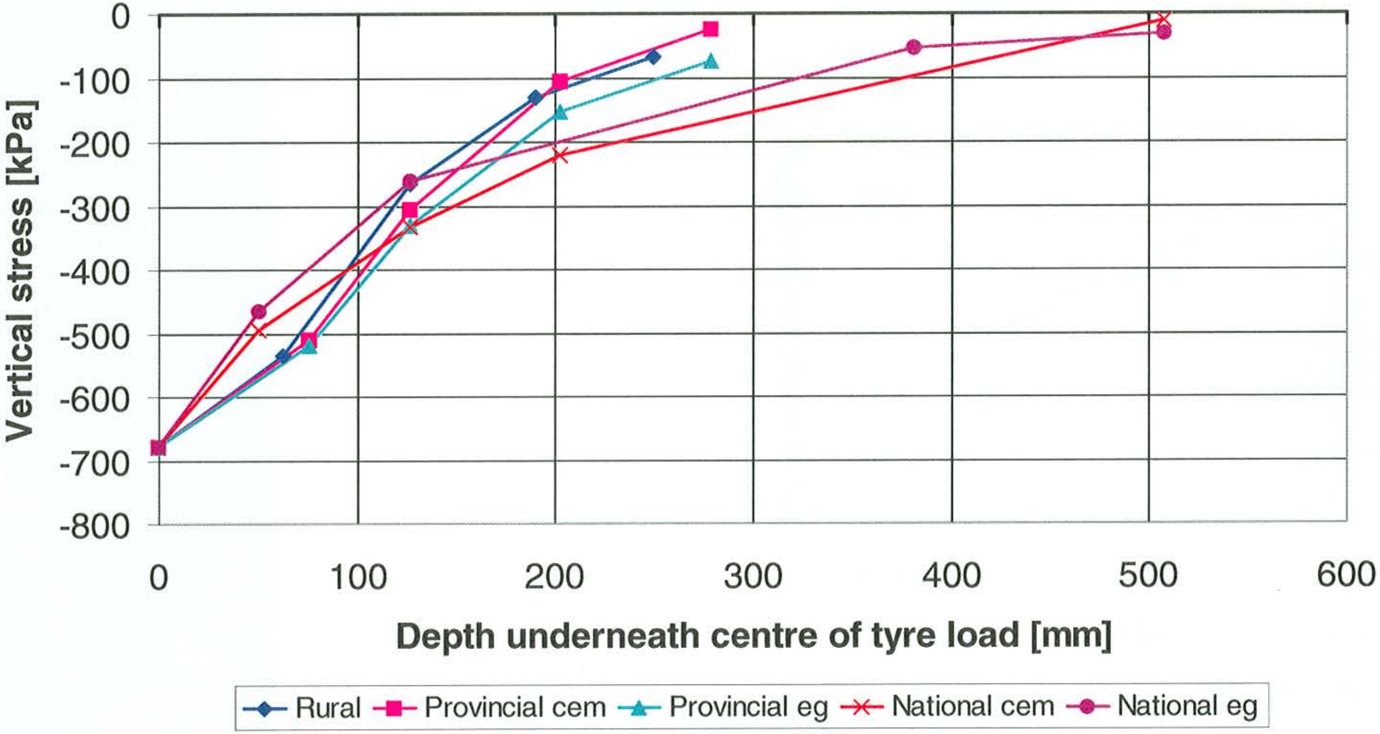


Figure 6.4: Typical vertical stress data (under centre of load) for pavements evaluated using 50th percentile static load.

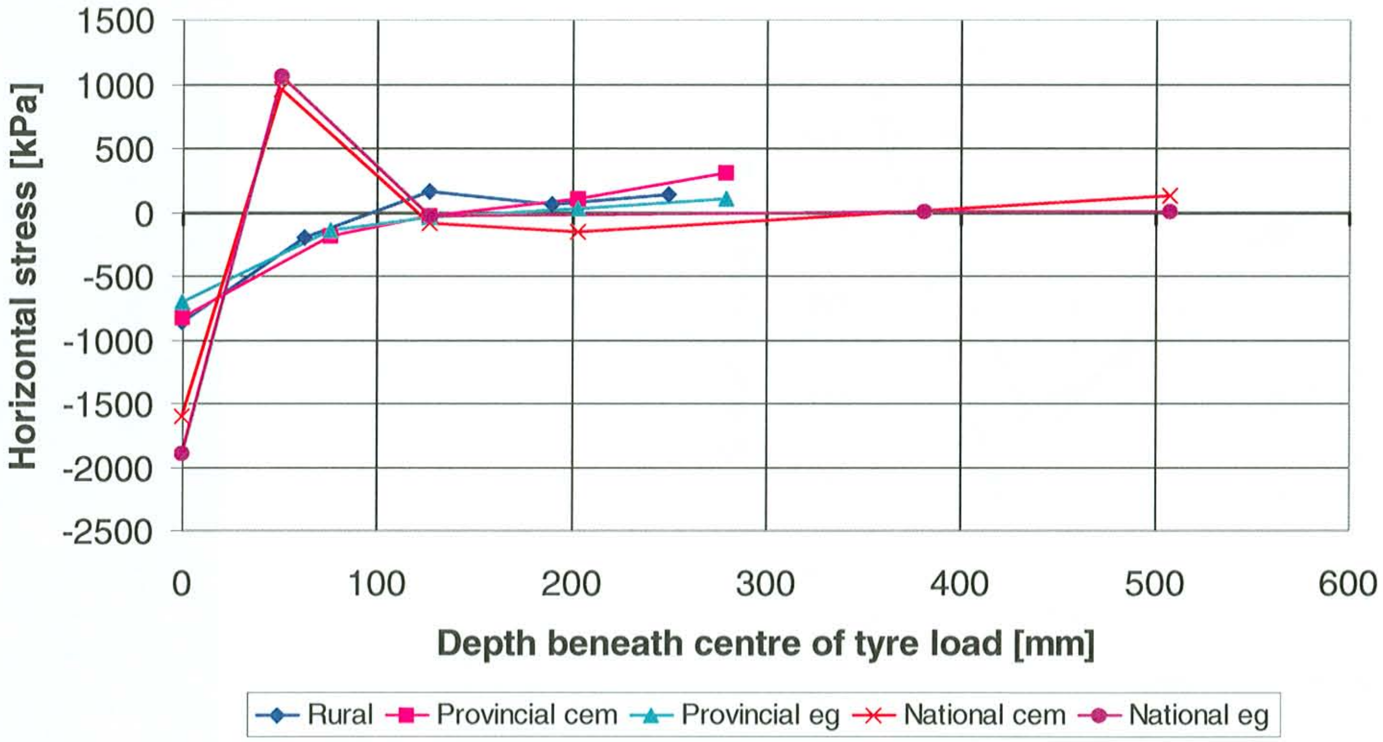


Figure 6.5: **Typical horizontal stress data (under centre of load) for pavements evaluated using 50th percentile static load.**

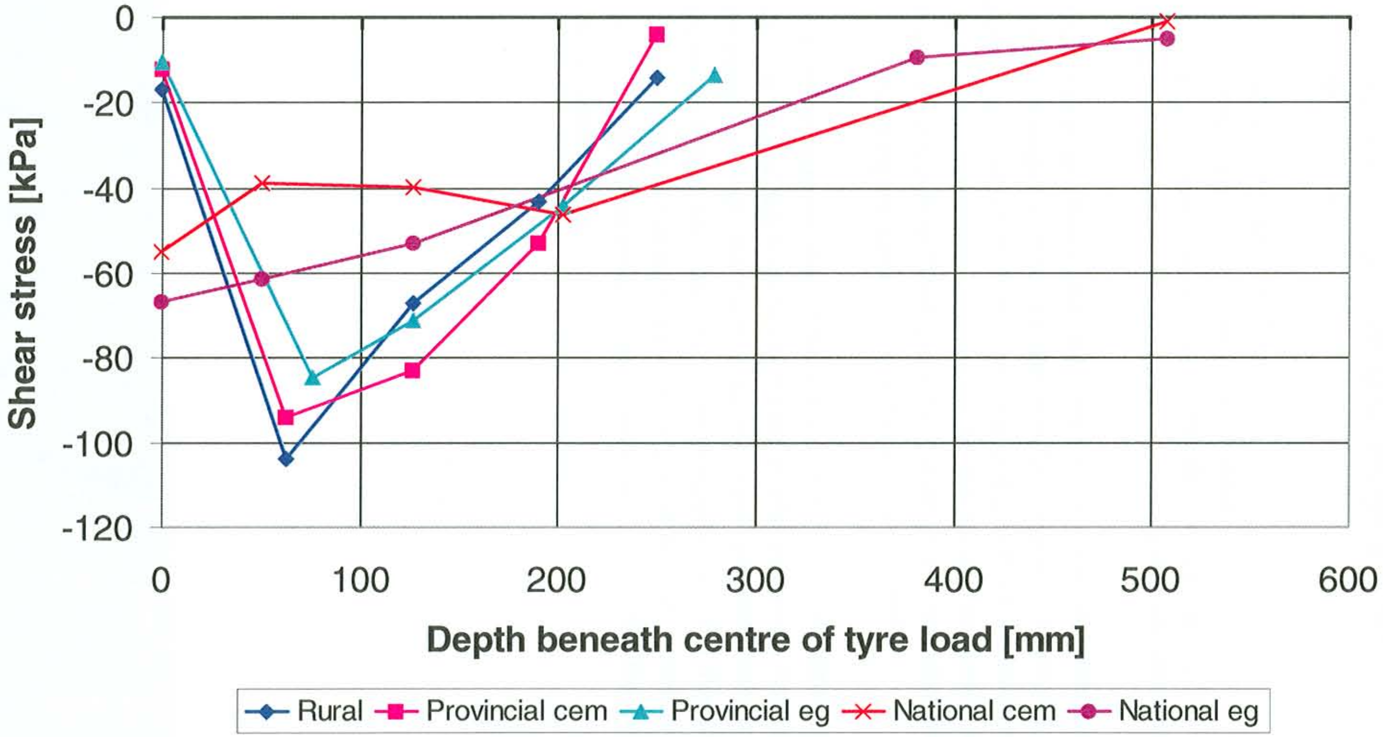


Figure 6.6: Typical shear stress data (under edge of load) for pavements evaluated using 50th percentile static load.

Ratios

The ratios between stresses, strains and deflections calculated at the four different load percentiles were evaluated to determine whether the changes in load magnitude caused similar changes in response. Similar patterns were found for all the pavements and parameters. The ratios between pavement response parameters for the four tyre load percentiles are shown in Table 6. 6. The ratios for the four load cases are also shown. The similar patterns evolve from the strong load dependence of the pavement response parameters shown in the statistical analyses.

Table 6.6: Ratios between tyre loads and pavement response parameters (stresses, strains and deflections) for static response analyses.

Load percentile [%]	Tyre load [kN]	Tyre load ratio	Pavement response parameter[a] ratio
50	21,3	1,00	1,00
80	23,8	1,12	1,12
90	24,4	1,15	1,15
95	33,6	1,58	1,58

a - stresses, strains and deflections

Statistical analysis

A statistical analysis between the calculated pavement response parameters and applied tyre loads confirmed the direct relationship between applied load and calculated response at all depths and positions.

6.2.3. Expected pavement lives

The stresses, strains and deflections discussed in Section 6.2.2 were used to calculate the expected pavement lives for each of the different load scenarios, using the SAMDM transfer functions. A summary of the critical lives in each pavement structure is shown in Table 6.7.

When these calculated expected lives are compared with the design traffic indicated in the design catalogue (TRH4) for the specific pavement structures, the calculated pavement classes (ES3 and ES0,3) for the rural and provincial pavements are similar to the design classes. The calculated expected life for the national pavement structure is higher than the design class shown in TRH4, but within the range of lives calculated for the specific pavement structure during the development of TRH4 (Theyse, 2000).

The critical expected lives indicated in Table 6.7 are all calculated under the 95th percentile load, as higher loads generally cause shorter pavement lives using the SAMDM transfer functions (although the norm is to use lower percentile values for rural roads, the same percentile values were used for all the comparisons in this thesis). The data indicate that the expected lives of the three pavements decreased with increased load percentiles. This is to be expected, as the stresses and strains used to calculate the expected lives from, increased with increased loads.

Table 6.7: **Summary of critical expected pavement lives based on ELSYM analyses and SAMDM transfer functions.**

Pavement structure (design traffic class)	Critical layer	Average expected life [million E80s] (traffic class)	Average total expected life [million E80s] (traffic class)
National (ES100)	C3	2,5 (ES3)	140 (ES100+)
National (equivalent granular)	G1	137 (ES100+)	
Provincial (ES3)	C4	1,2 (ES3)	1,2 (ES3)
Provincial (equivalent granular)	EG5	0,88 (ES1)	
Rural (ES0,3)	G6	0,01 (ES0,03)	0,01 (ES0,03)

6.2.4. Summary of static pavement response analyses

The results from the static pavement response analyses indicate that similar trends can be expected from the various pavement response parameters for each of the pavement structures investigated at the various tyre load percentiles. Increased load magnitude (percentile) resulted in increased stresses, strains and deflections. A perfect linear relationship exists between the load magnitudes and the calculated pavement response parameters. The applied loads influence the expected lives of the various layers in the pavements critically.

6.3. Transient Response Analysis

6.3.1. Introduction

The transient response analysis was performed as the advanced pavement response analysis tool using two finite element methods. It involved a 2-dimensional axi-symmetric package (Jooste, 1999). Attempts were made to also use a 3-dimensional finite element package to evaluate the transient response of a pavement as loaded by a set of moving dynamic loads, representing a full vehicle. However, it proved to be technically complicated, and was therefore left out of this thesis. Issues around performance of 3-dimensional MDL analyses and the expected results thereof are, however, addressed in Section 7.4. There are also recommendations made towards performing such an analysis.

All the load cases were analysed using the 2-dimensional method. The 2-dimensional analysis involved a Moving Constant Load (MCL) analysis. The 2-dimensional analysis involved a load that moved but did not change load magnitude (see Section 4.2.2 and 4.2.3 for detailed definitions). The term transient response analysis is used in this thesis for the finite element analysis.

Only the data for the left wheeltrack steering tyre were used. This was to enable comparison with the data obtained from the static response analysis. In this process exact tyre loads (as opposed to equivalent tyre loads from dual tyre sets) were used for the analyses.

The inferences drawn from the load cases analysed using only the MCL method focus only on the transient response of the pavement to a single tyre load. It is recommended that these load cases be analysed using a 3-dimensional approach when the costs are within a specific project's scope.

The tyre loads used for the MCL analyses originate from the tyre load distribution obtained from evaluating all the moving tyre loads of all three vehicles at the three load conditions defined in Chapter 5. The specific loads are shown in Tables 5.6 and 6.8. Tyre loads at the 50th, 80th, 90th and 95th percentile values are used as input data. The correspondent axle load (assuming a single axle with dual tyres) and equivalent 80 kN load (assuming an exponent of 4,0) for each of the load cases are shown in Table 6.8. The difference between the tyre loads in Table 6.8 and the static tyre loads in Table 6.1 is that the tyre loads in Table 6.1 were measured while the vehicles were standing still, while those in Table 6.8 were measured while the vehicles were moving.

Table 6.8: **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

The pavement structures on which the analyses were performed are shown in Tables 4.4 and 6.2. The material properties used for each of the layers are shown in Table 4.5. The national and provincial road structures (which include cemented layers) were again evaluated using two phases (a cemented and equivalent granular phase).

The asphalt surfacing stiffness (2 980 MPa) shown in Table 4.5 was used as the static stiffness (elastic modulus) of the asphalt surfacing on the national pavement structures. The Asphalt Institute Formulas for calculating dynamic modulus of asphalt layers, as referenced by Huang (1993), were used to calculate the dynamic asphalt modulus at the speeds at which the pavement response analyses were performed. The calculated stiffnesses at the indicated speeds are shown in Table 6.9.

Table 6.9: **Calculated dynamic stiffnesses for asphalt surfacing of national pavements using Asphalt Institute formulas.**

Load speed [km/h]	40	60	80	90	100
Dynamic stiffness [MPa]	5 568	6 588	7 611	8 138	8 681

A linear elastic material model was used for the transient response analysis method. The reasons for this decision were to enable direct comparison with the current standard pavement response analysis (static response analysis using ELSYM5M), to keep the variables between the two pavement response analysis methods to a minimum, and because an investigation into the non-linear response of pavements to loads is outside the scope of this thesis (see Section 4.5.3). However, this does not mean that the aspect of non-linear material response is trivial or not important. The additional value of doing a non-linear material response analysis will mainly lie in a more realistic representation of the response of the pavement to loading, especially in terms of permanent deformation. The additional cost of this exercise (in terms of additional input parameters, longer response calculation times and more complicated data reduction and analysis techniques) must also be accounted for. Further, the current SAMDM transfer functions only make provision for pavement responses calculated using linear elastic material response parameters.

The meshes used for each of the three pavements in the MCL analyses consisted of between 100 (rural and provincial pavements) and 130 (national pavement) elements. Each of these 2-dimensional meshes was 4 064 mm wide and 4 064 mm deep, and was constrained at its edges. The smallest elements were 25,4 mm x 25,4 mm in size. These elements were located underneath the applied load.

The process used to calculate the pavement response under a moving tyre load consisted of applying the tyre loads at fixed positions on the pavement surface, and monitoring of the pavement responses at positions in the pavement equivalent to the distance from the loaded areas at the required speed.

The MCL analyses were performed using an axi-symmetric finite element package (Owen and Hinton, 1980). The load was applied to the pavement as a sinusoidal pattern that was applied for a time equivalent to the time required to cover the tyre patch area (assumed as a 200 mm diameter circle) at the speed for which the analysis was performed. The pavement responses were then monitored at various nodes on the mesh at times equivalent to the time for the tyre load to travel the distance at the speed at which the analysis was performed. This method caused the response of the pavement to be equivalent to that for a pavement over which the load is moving. The concept is shown schematically in Figure 6.7.

The time required to move between two nodes on the finite element mesh at the analysis speed was used to decide which of the time steps' data at a specific position should be used in the calculation.

The pavement responses were monitored at specific depths in the pavement. These depths coincided with interfaces between layers as well as the positions at which stresses and strains are required in the SAMDM analyses. The specific depths at which pavement response was monitored for each of the pavements are shown in Table 6.10. As the positions for the MCL analyses coincided with Gauss points in the elements, they are not similar to the positions of the mesh nodes.

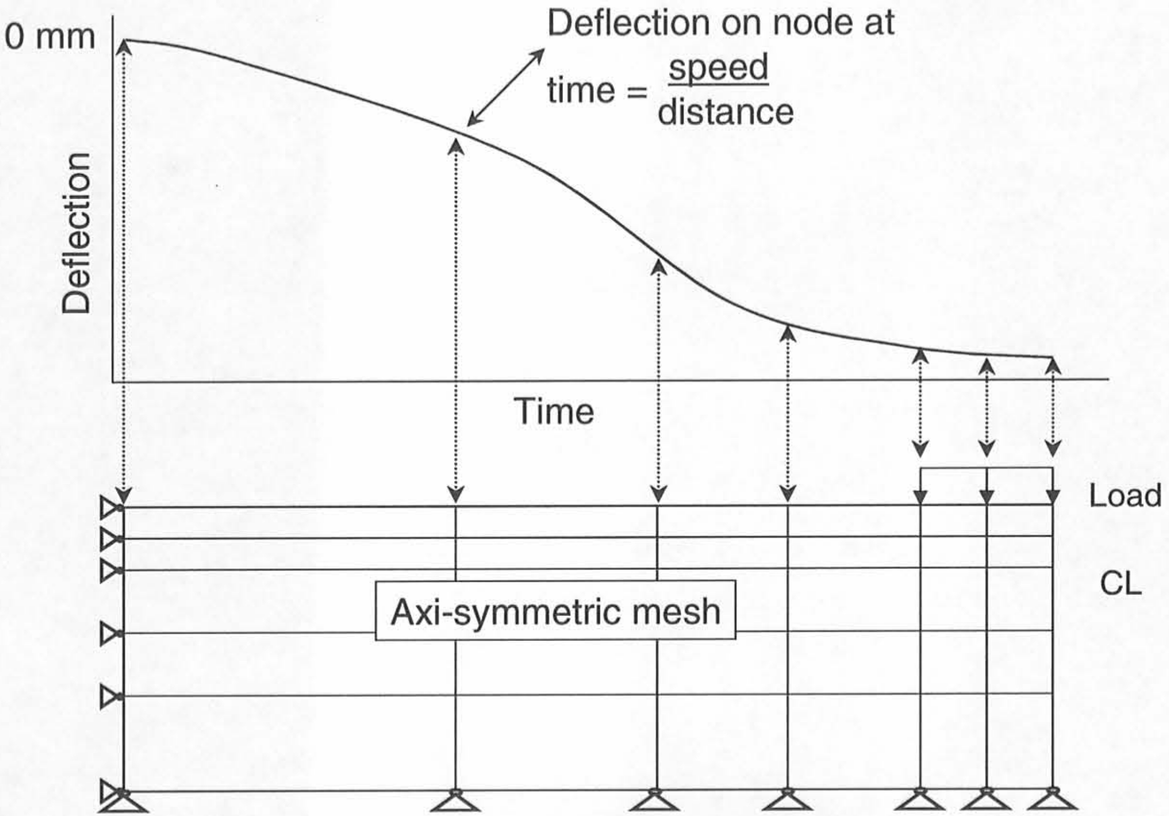


Figure 6.7: Graphical explanation of development of deflection bowls from axi-symmetric finite element data using superposition method.

Table 6.10 **Depths at which stresses and strains were calculated for each pavement structure.**

	National road structure	Provincial road structure	Rural road structure
Depth below centre of tyre load [mm]	7 mm	7 mm	7 mm
	42 mm	58 mm	58 mm
	58 mm	91 mm	91 mm
	109 mm	109 mm	109 mm
	211 mm	152 mm	147 mm
	348 mm	178 mm	170 mm
	414 mm	229 mm	211 mm
	450 mm	254 mm	234 mm
	567 mm	363 mm	338 mm

6.3.2. Analyses output

The results from the MCL analyses are shown and discussed in this section. In Section 6.4 these results are compared with results from the static response analyses.

The standard outputs from the MCL analyses are vertical deflection, vertical, horizontal and shear stresses and vertical, horizontal and shear strains. Figures 6.8 to 6.22 show the maximum values of the pavement response parameters at the indicated depth for the 50th percentile load case. It also shows changes with time for the stresses calculated. The strains were not calculated directly in the software, but at selected positions and time intervals and are therefore not plotted against load time. The figures of stress against time are for the rural pavement with a 95th percentile load. The actual load duration time is also indicated. The last set of figures indicates the change in response parameters against speed.

Elastic vertical deflection

A typical relationship between elastic vertical deflection and load speed for the range of pavement structures is shown in Figure 6.8. The elastic surface deflections calculated decreased with increased load speed and increased with increased load magnitude. The major part of the decrease related to load speed occurs before a load speed of 40 km/h is reached. At higher load speeds the decrease is less prevalent. This phenomenon was measured by Lourens (1995) and it appears that most of the reduction occurs at speeds lower than 40 km/h. This was, however, outside the range of speeds investigated in this thesis.

The elastic vertical deflection values ranged between 0,18 mm and 0,50 mm for static loads, while the values ranged between 0,03 mm and 0,12 mm at load speeds of 100 km/h. The highest deflection was calculated for the provincial ***eg***, rural and national ***eg*** pavements, which contained only granular layers in their structures. In Figure 6.9 typical deflection bowls at 40 km/h and 100 km/h are shown for the provincial pavement. The phase difference in the position of the maximum deflection is apparent from the figure. The difference in maximum deflection at the two speeds is also visible. The staggered shape of the graphs is due to the superposition method used to develop the moving load deflection bowls from the axi-symmetric finite element method results (as discussed earlier).

Vertical stress

A typical relationship between vertical stress and load speed for the range of pavement structures is shown in Figure 6.10. Similar trends were observed at all load magnitudes. Compressive vertical stresses were calculated in all layers of the pavement structures. The vertical stresses at the surface of the pavement correlated well with the applied load pressures. Vertical stresses decreased with increasing depths except for the national ***cem*** and ***eg*** pavements. Higher vertical stresses were calculated at the bottom of the relative stiff asphalt surfacing. Vertical stresses decreased slightly with increasing load speeds for the national (***cem*** and ***eg***) and provincial (***cem*** and ***eg***) pavements (Figure 6.11). The vertical stresses for rural pavements increased again at speeds higher than 40 km/h. These increases in vertical stress with increased load speeds, correlates with the typical decreases in vertical elastic deflection with increased speeds. In Figure 6.12 typical vertical stress response with time as calculated from the MCL analyses are shown.

Horizontal stress

A typical relationship between horizontal stress and depth for the range of pavement structures is shown in Figure 6.13. Similar trends were observed in the data at all load percentiles. Compressive horizontal stresses were calculated in all layers of the pavement structures. The stress magnitude increased with increased applied tyre loads. The stress magnitudes were lower deeper into the pavement structure, and the rates of decrease in stress magnitude were also less dramatic at these depths. In Figure 6.14 the typical relation between the horizontal stress and speed is shown. These stresses decreased between 0 and 40 km/h, and remained relatively constant for further speed increases. In Figure 6.15 a typical horizontal stress response with time as calculated from the MCL analyses is shown.

Shear stress

A typical relationship between shear stress and depth for the range of pavement structures is shown in Figure 6.16. Similar trends were again observed at all load percentiles investigated. Compressive shear stresses were calculated in all layers. The stress magnitude increased with increased applied tyre loads. Stress magnitudes stayed relatively constant at speeds higher than 40 km/h (Figure 6.17). The national (***cem*** and ***eg***) and provincial ***eg*** pavements showed decreasing stresses between 0 and 40 km/h, while the stresses in the rural and provincial ***cem*** pavements remained relatively constant. The effect of load speed on stress magnitude was less dramatic than the effect of load magnitude. In Figure 6.18 a typical shear stress response with time as calculated from the MCL analyses is shown.

Horizontal strain

Typical horizontal strain responses against depth are shown in Figure 6.19 for the different pavement structures investigated. Similar trends were observed for all the load percentiles investigated. Tensile horizontal strains were calculated in all pavements analysed. These strains decreased with increasing depths. The provincial ***eg*** pavement yielded the highest strains in the upper 150 mm of the pavement. Similar trends were observed in the rural and provincial (***cem*** and ***eg***) pavements with decreasing strains at increasing depths. The national pavement (***cem*** and ***eg***) yielded lower horizontal strains at the surface than under the asphalt surfacing and in the centre of the granular G1 base layer. This may be attributed to the very stiff asphalt surfacing incorporated in these pavements. In Figure 6.20 the horizontal strain is shown against increasing speed. The rural and provincial ***eg*** pavements showed increases in horizontal strain against increases in speed, while the strains for the other three pavements showed slight increases with increasing speeds. The maximum horizontal strains all changed from compressive strains to tensile strains with increases in speed.

Vertical strain

Typical vertical strain responses are shown in Figure 6.21. Similar trends were observed at all the load percentiles. The vertical strains for the rural and provincial pavements (***cem*** and ***eg***) decreased with increased depths. The national (***cem*** and ***eg***) pavements initially yielded increasing strains (through the asphalt surfacing layer) and deeper down in the pavement relatively constant strains. The initial increase in strain may be attributed to the effect of the stiff asphalt surfacing on calculated vertical strains. The provincial ***eg*** pavement yielded the highest vertical strains in the upper parts of the pavement (up to 150 mm). The vertical strains on top of the subgrades, from which the subgrade lives are calculated using the SAMDM transfer functions (Theyse et al, 1996) were similar for all pavements.

In Figure 6.22 the vertical strain is shown against increasing speed. All the pavements showed decreases in vertical strain with increases in speed. The provincial ***eg*** and rural pavements showed the highest compressive strains, with the national pavement (***cem*** and ***eg***) the lowest strains. The majority of the decrease in strain occurred between 0 and 40 km/h.

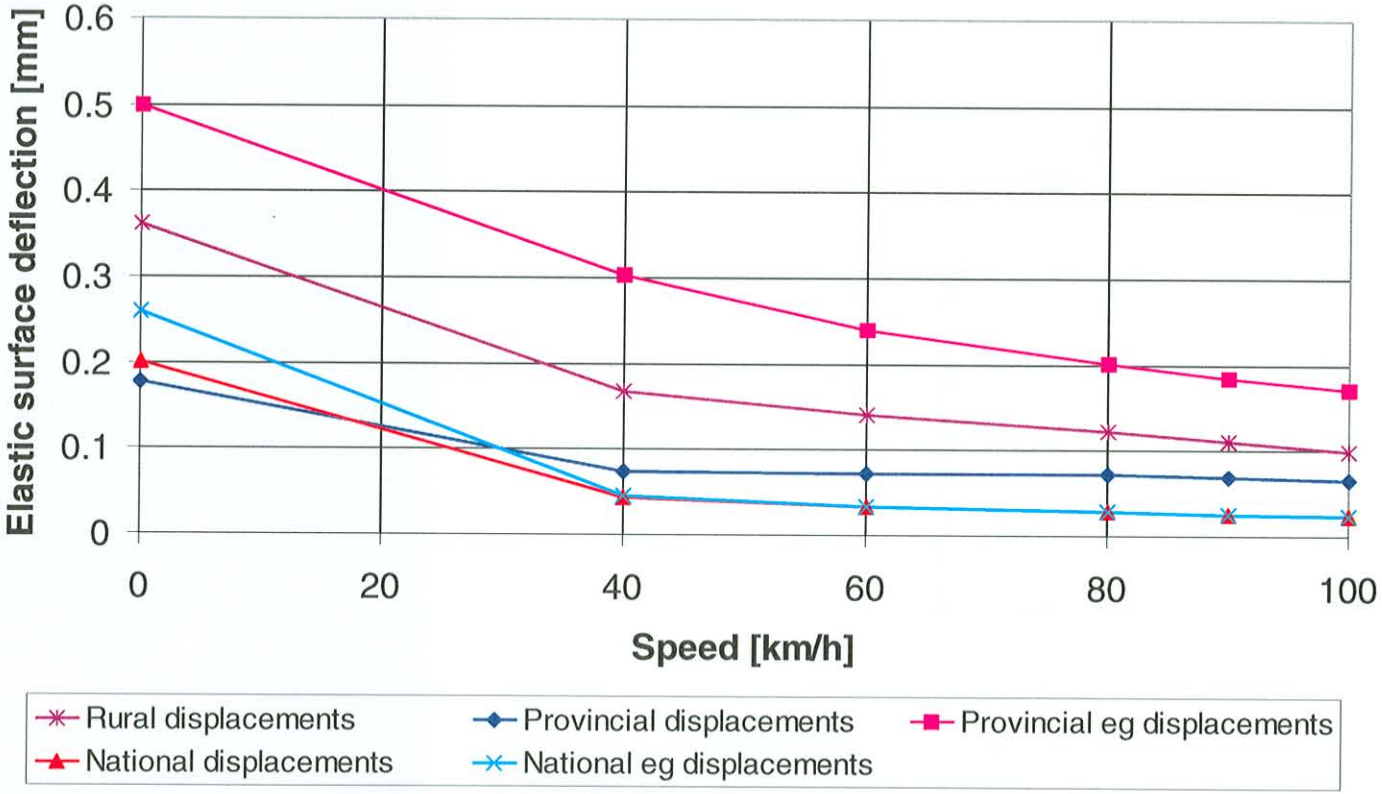


Figure 6.8: **Typical elastic surface deflections (50th percentile loads) as calculated using MCL method.**

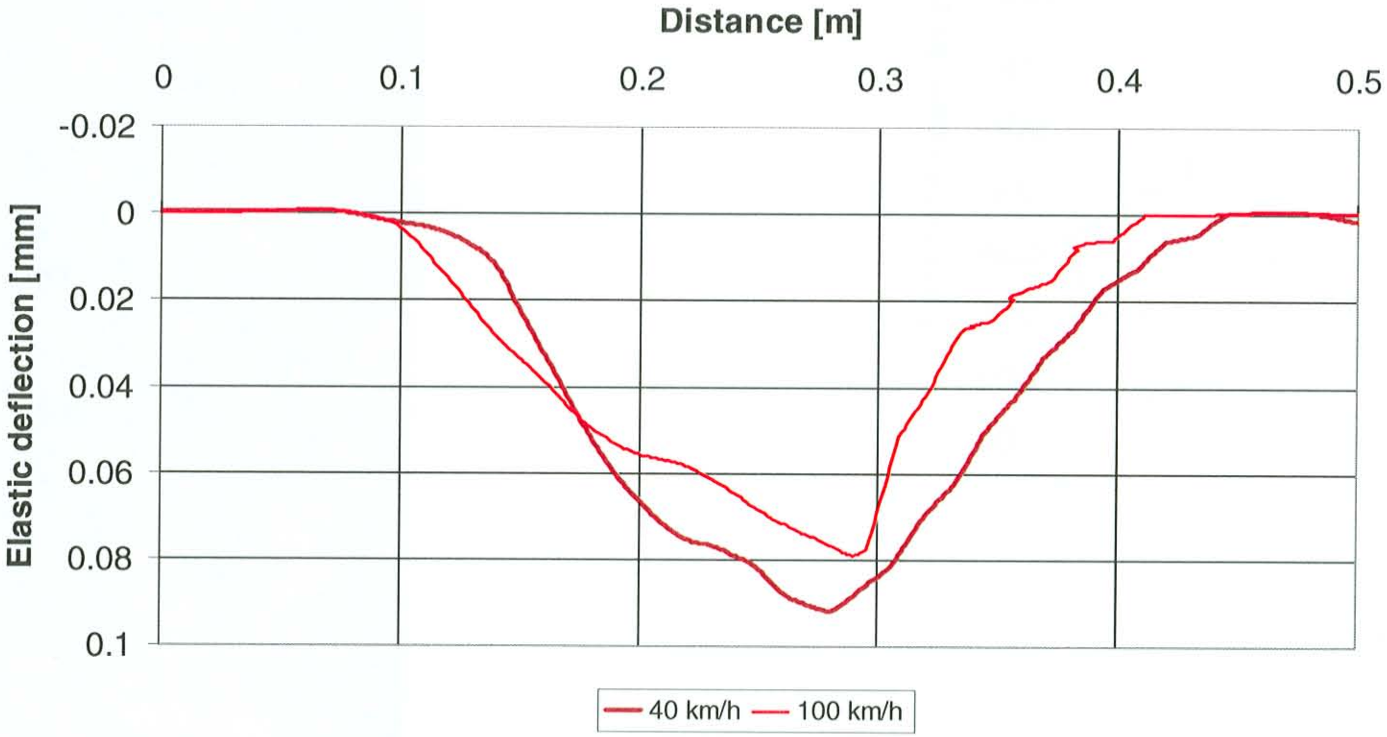


Figure 6.9: **Typical elastic surface deflection bowls (90th percentile loads) on provincial cemented pavement) as calculated using MCL method.**

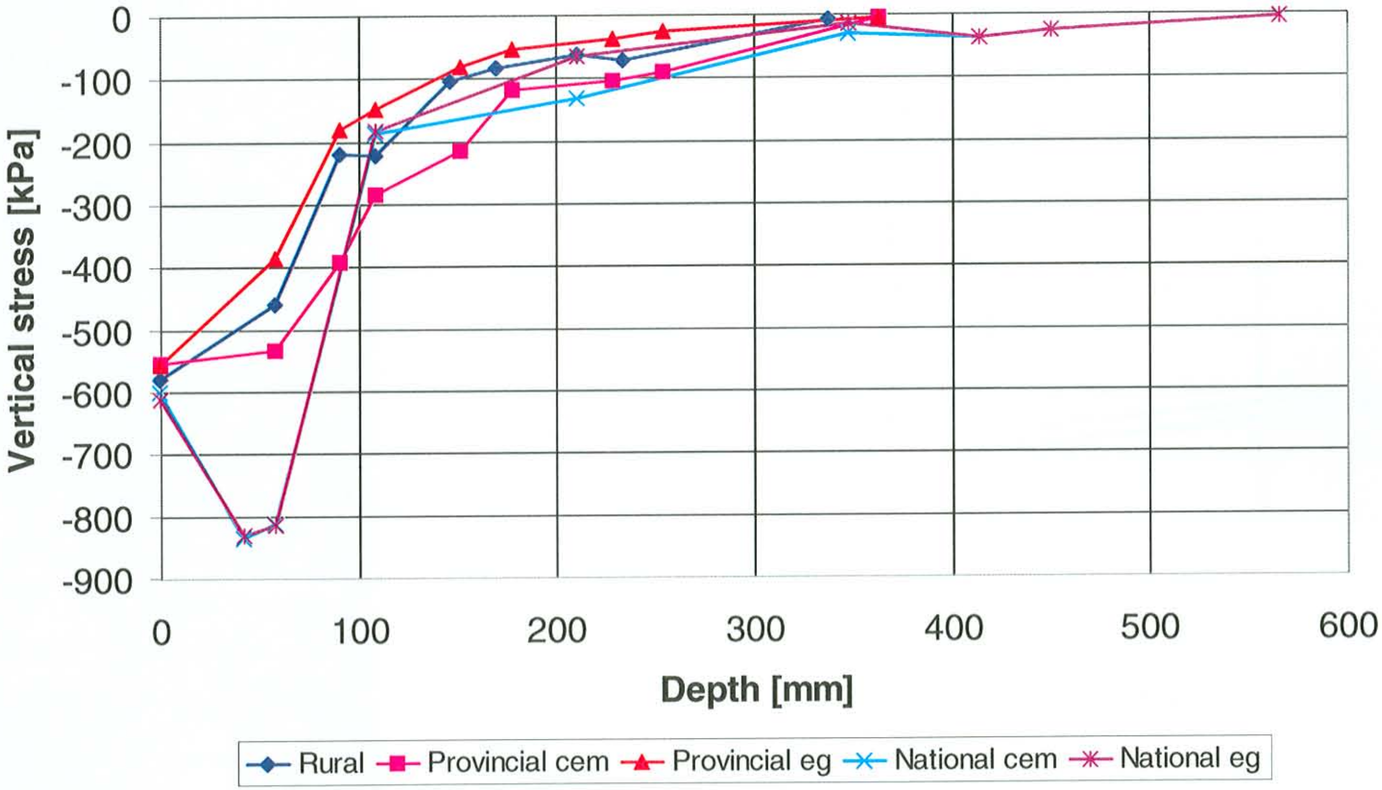


Figure 6.10: Typical vertical stresses (50th percentile load) as calculated using MCL method.

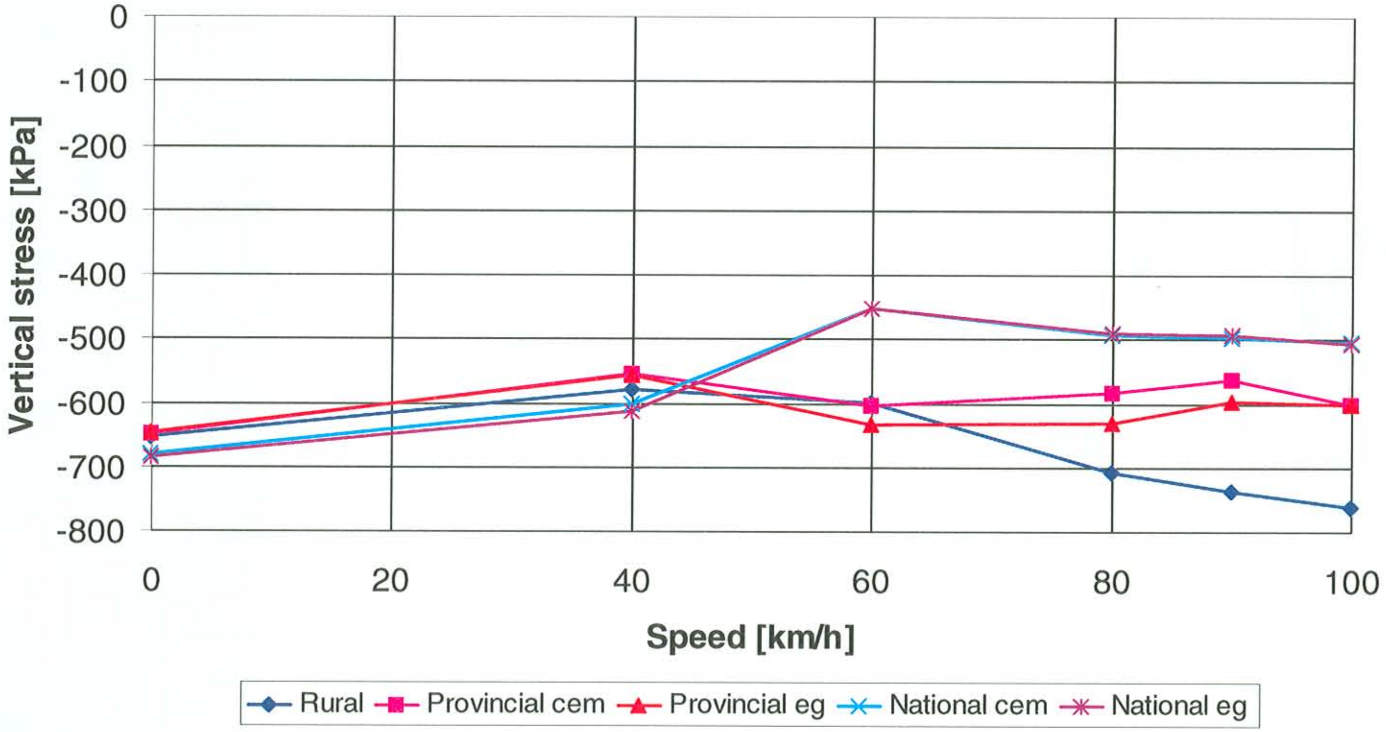


Figure 6.11: Typical vertical stresses against speed (50^{th} percentile load) as calculated using MCL method.

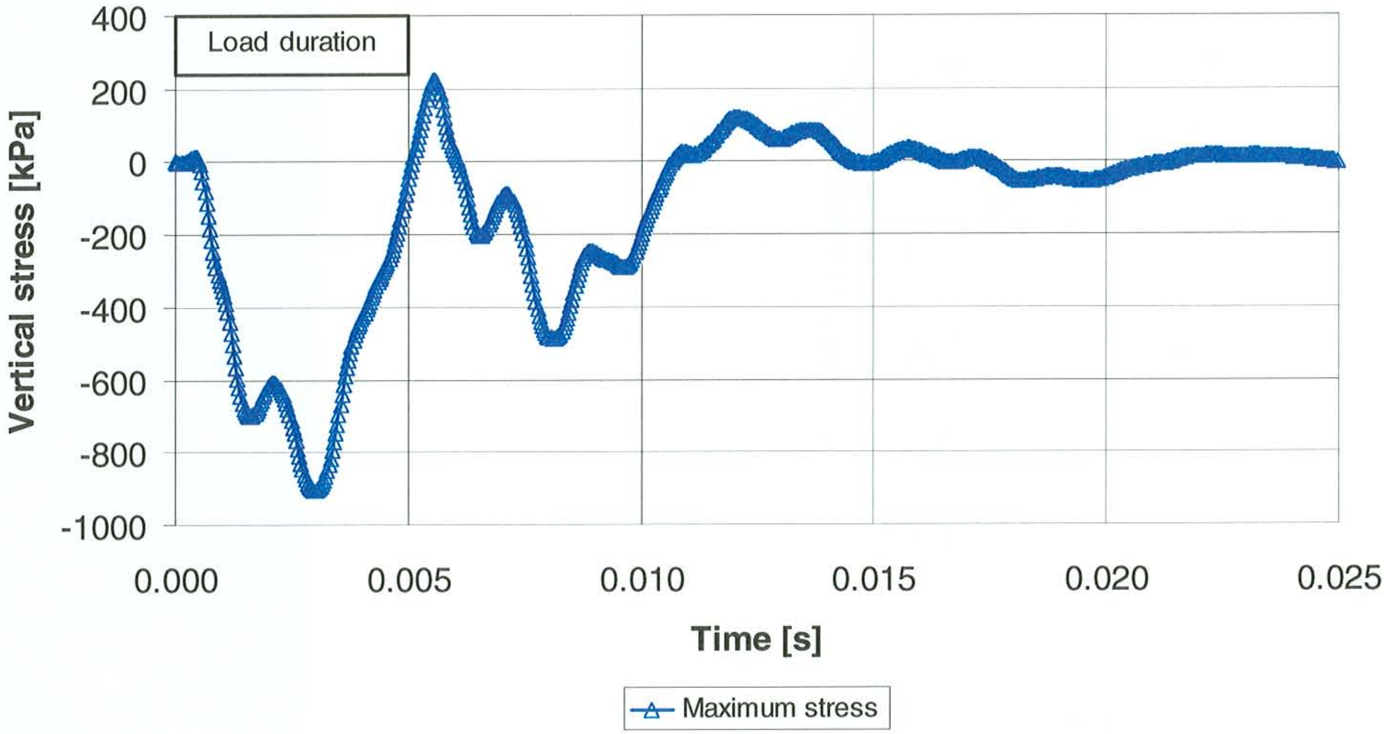


Figure 6.12: Typical vertical stresses (95th percentile load) as calculated using MCL method for rural pavement structure.

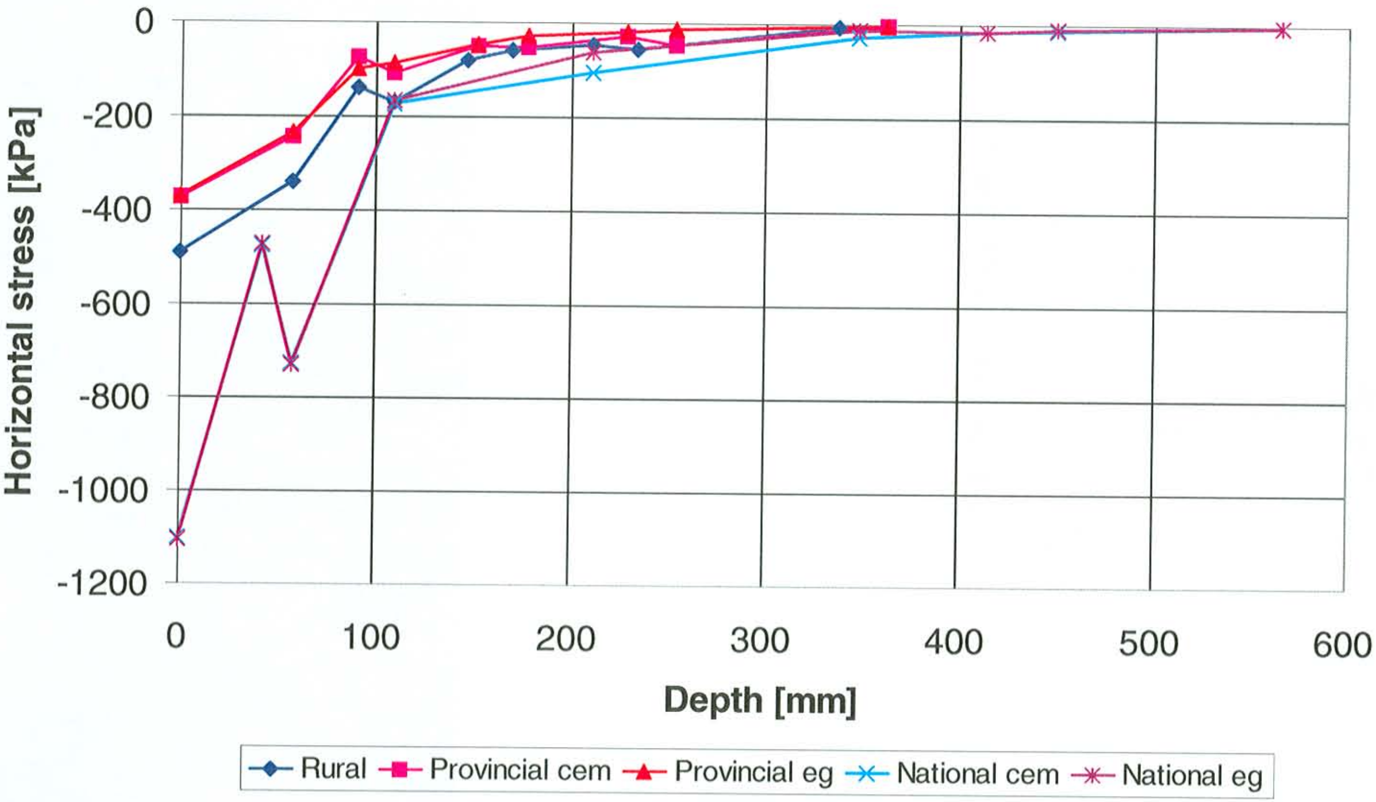


Figure 6.13: Typical horizontal stresses (50th percentile load) as calculated using the MCL method.

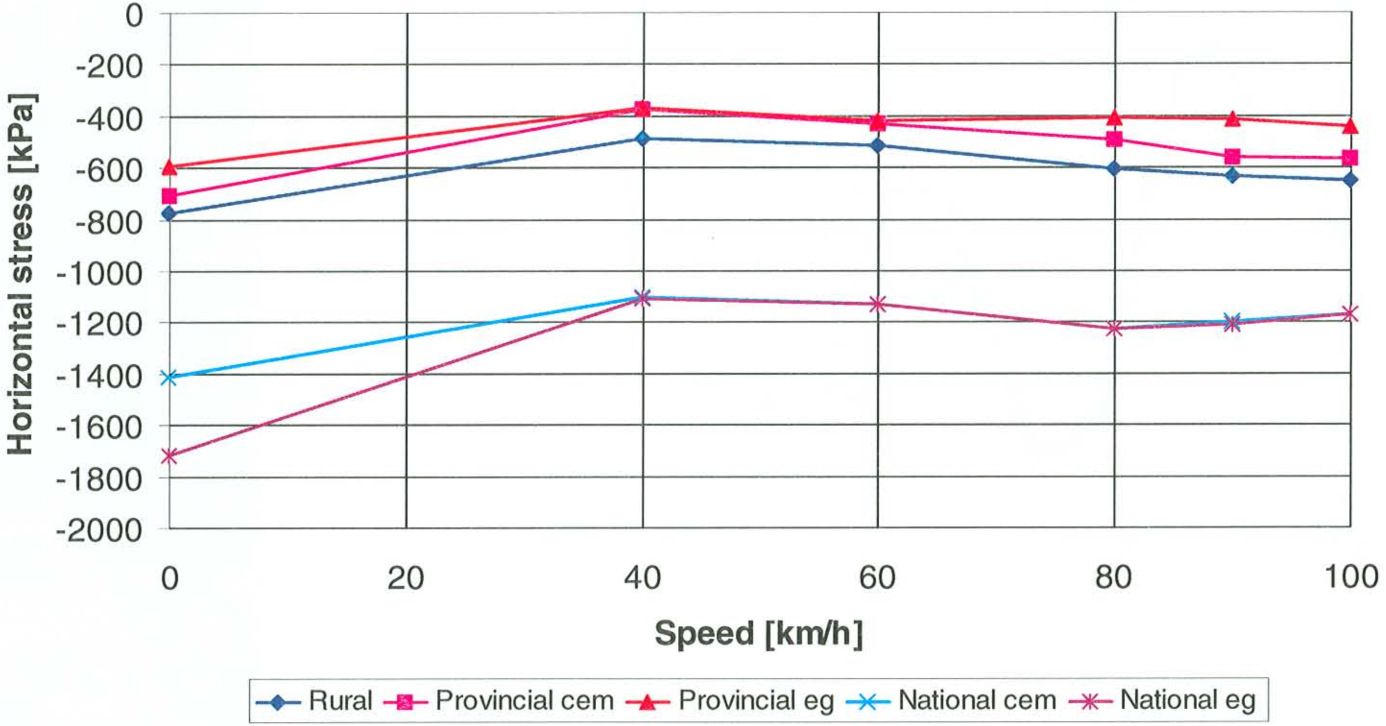


Figure 6.14: **Typical horizontal stresses (50th percentile load) against speed as calculated using the MCL method.**

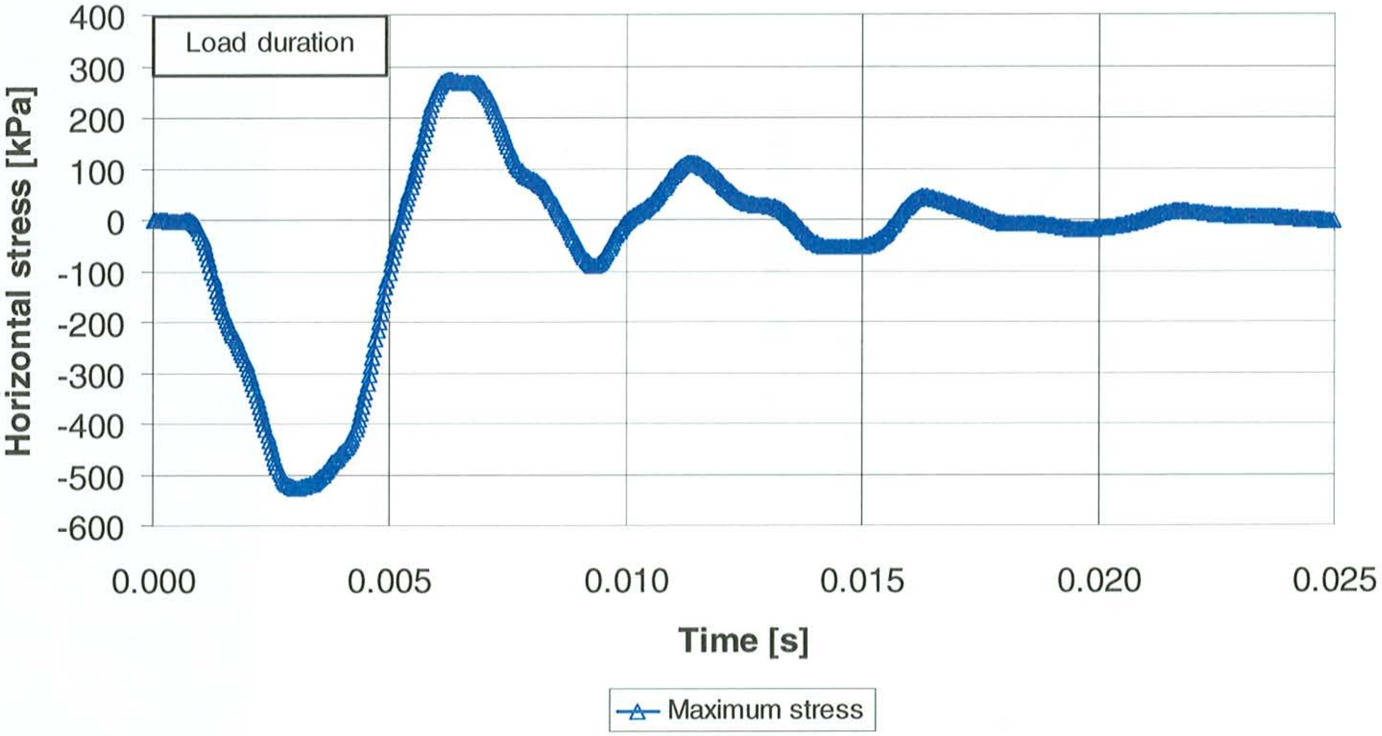


Figure 6.15: Typical horizontal stresses (95th percentile load) as calculated using the MCL method for a rural pavement structure.

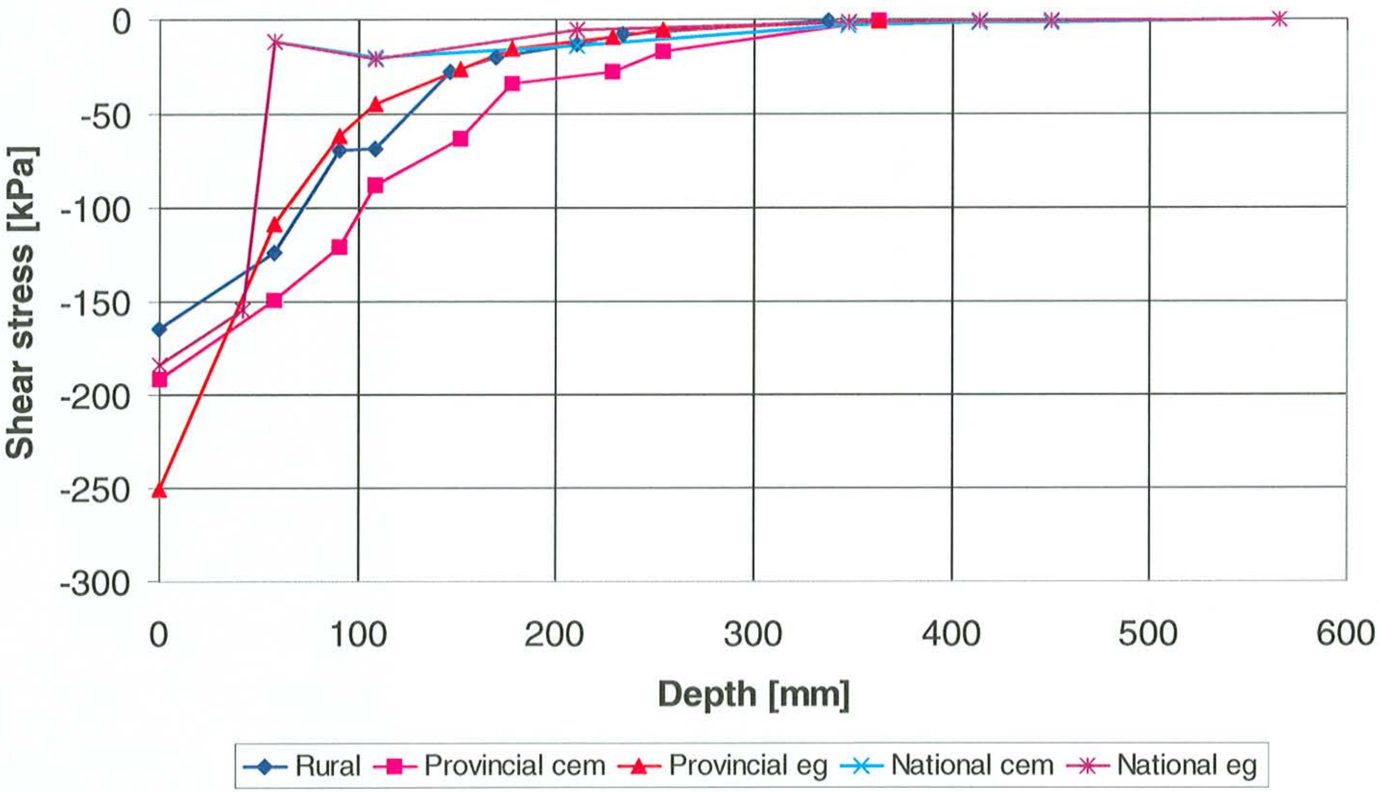


Figure 6.16: Typical shear stresses (50th percentile load) as calculated using the MCL method.

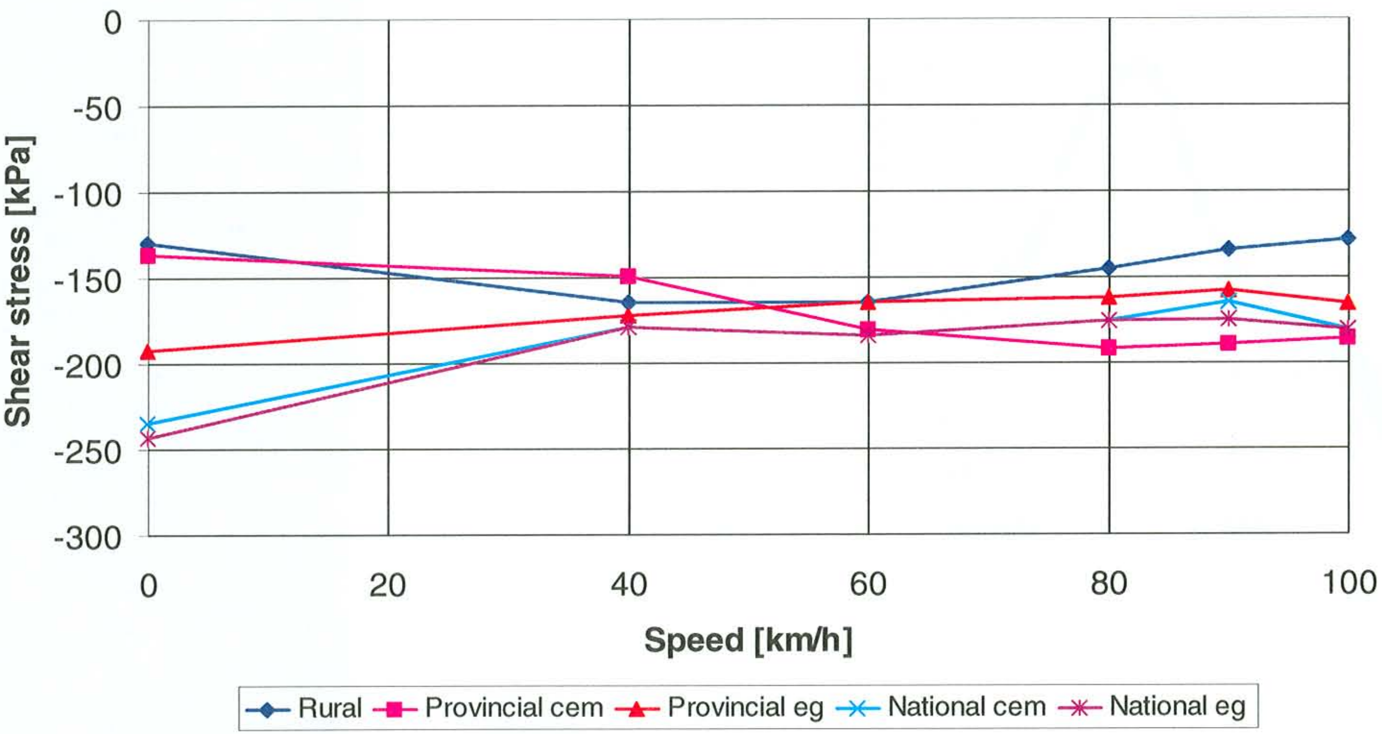


Figure 6.17: Typical shear stresses (50th percentile load) against speed as calculated using the MCL method.

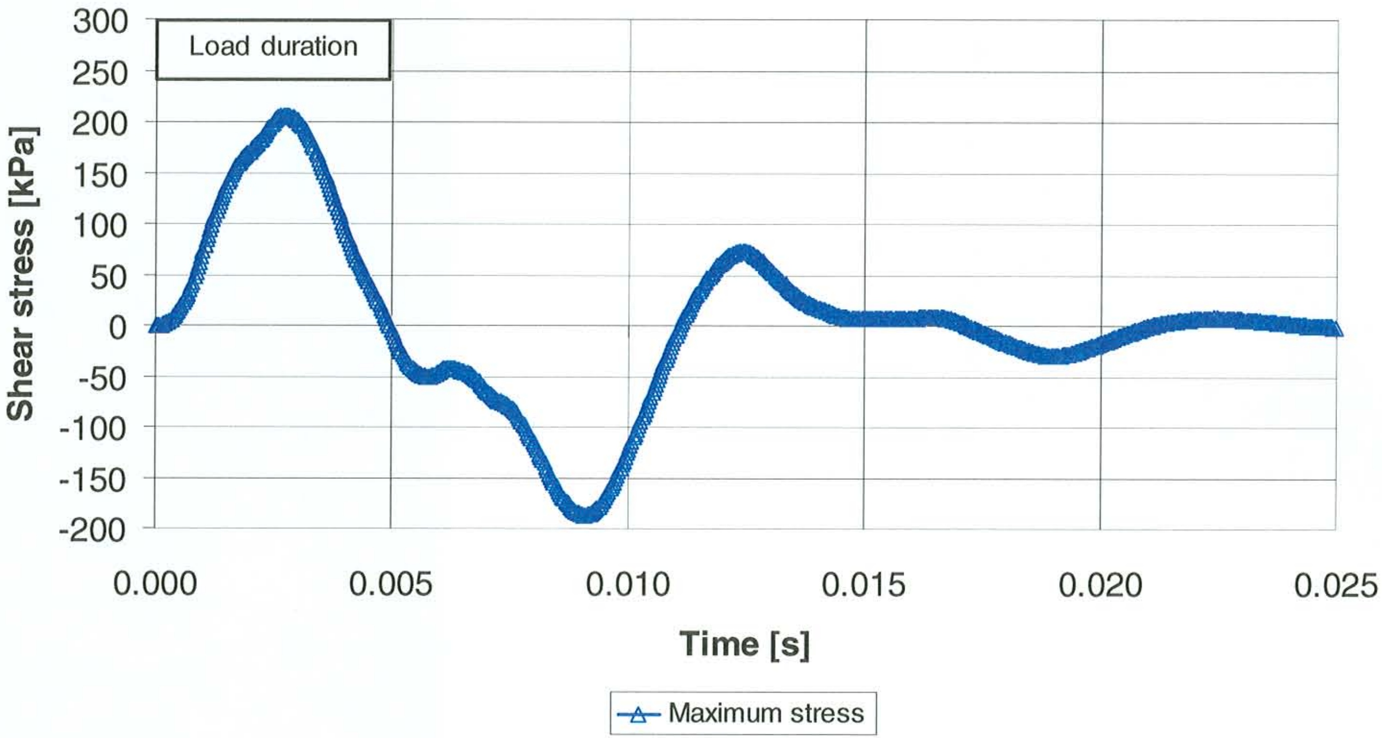


Figure 6.18: **Typical shear stresses (95th percentile load) as calculated using the MCL method.**

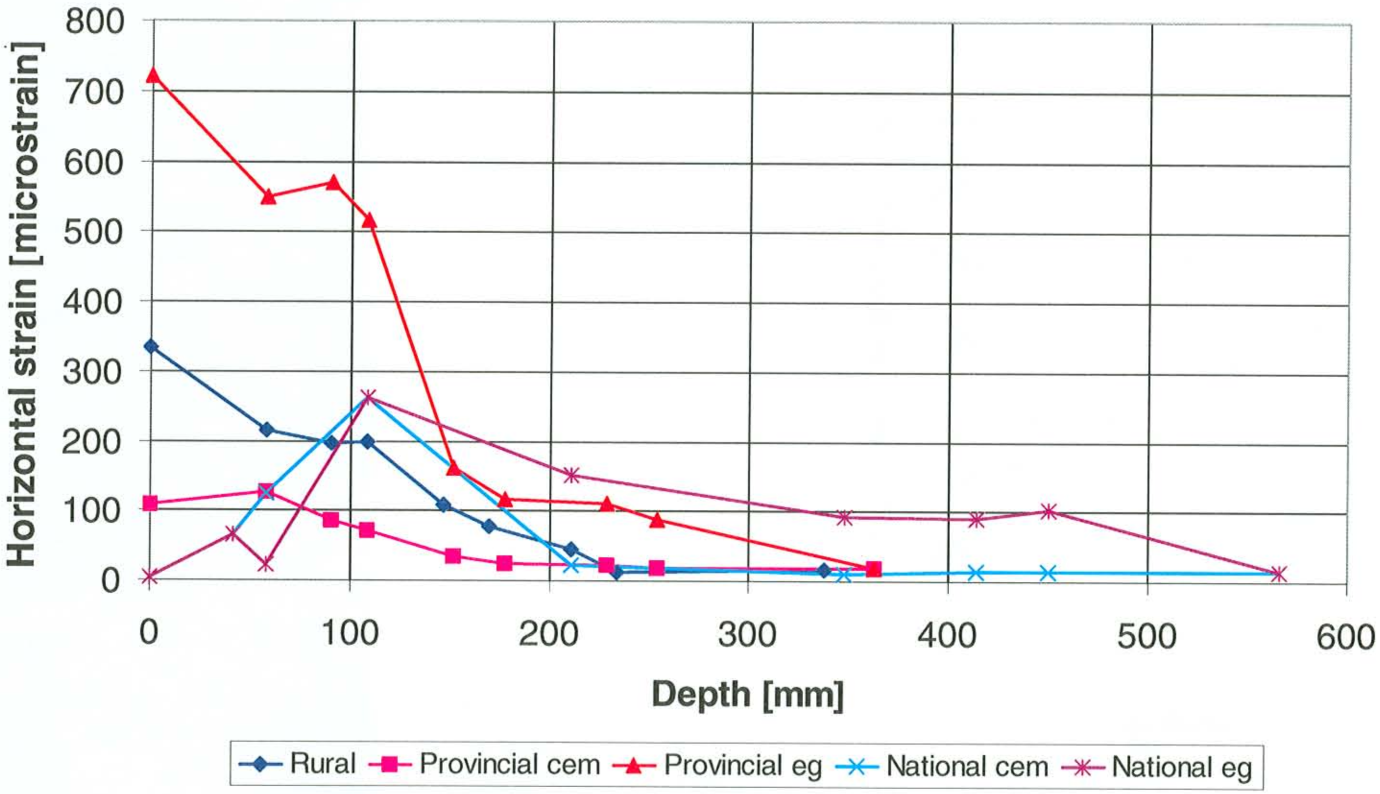


Figure 6.19: Typical horizontal tensile strain (50th percentile load) as calculated using the MCL method.

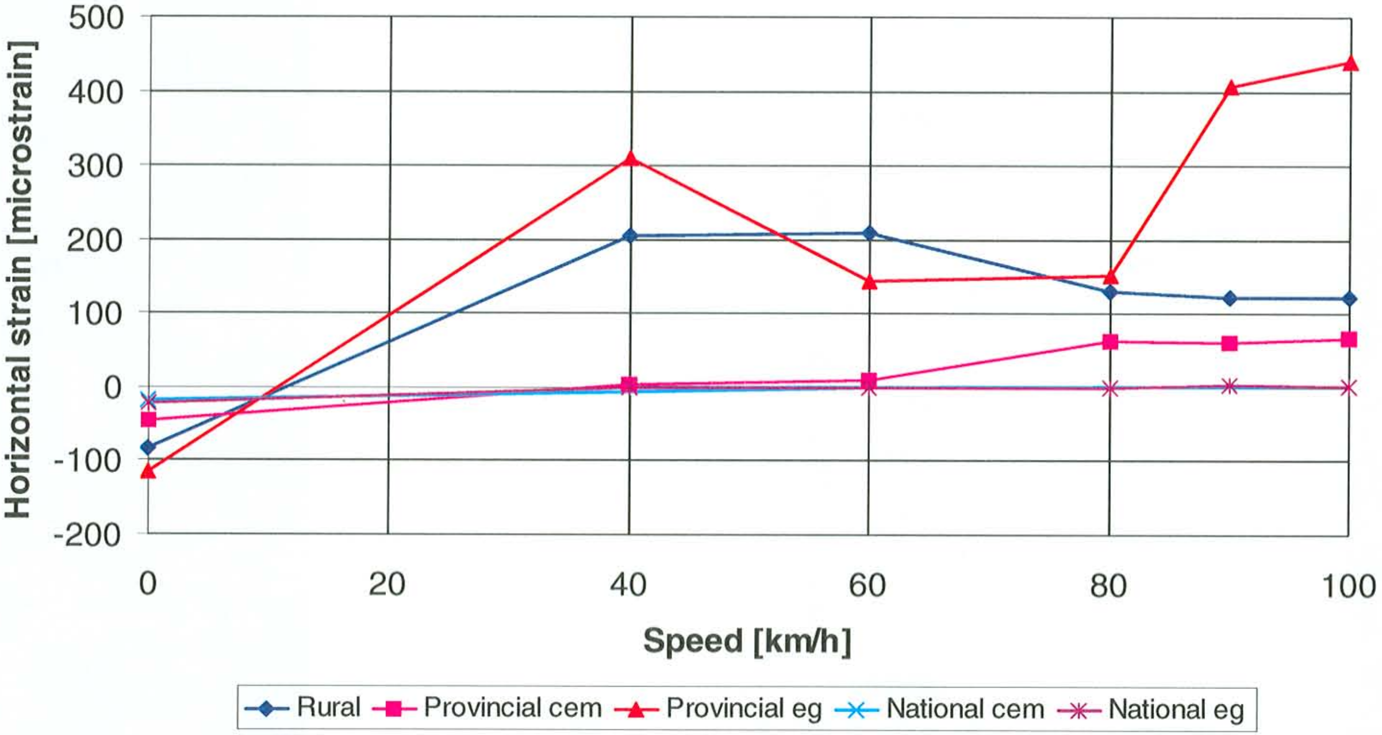


Figure 6.20: Typical horizontal strain (50th percentile load) against speed as calculated using the MCL method.

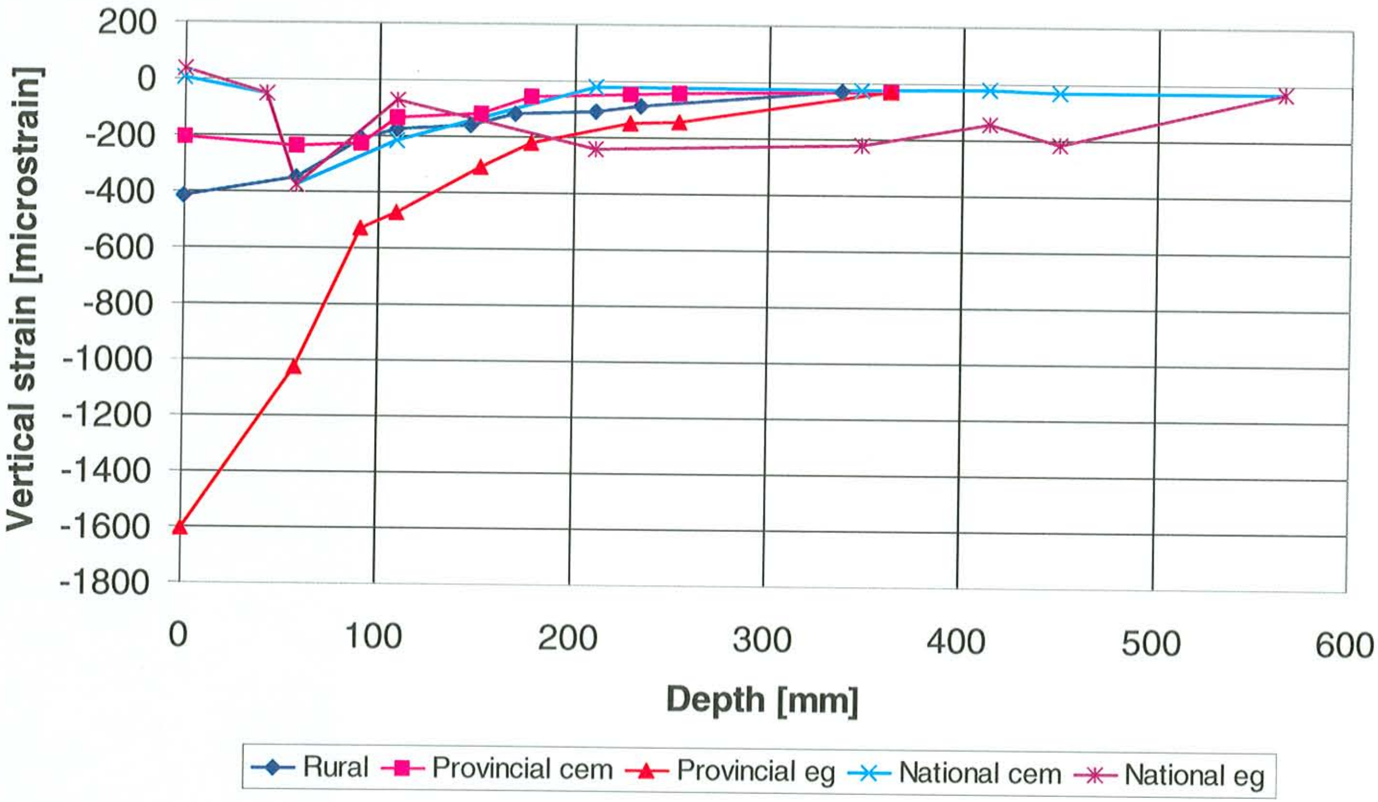


Figure 6.21: Typical vertical compressive strain (50th percentile load) as calculated using the MCL method.

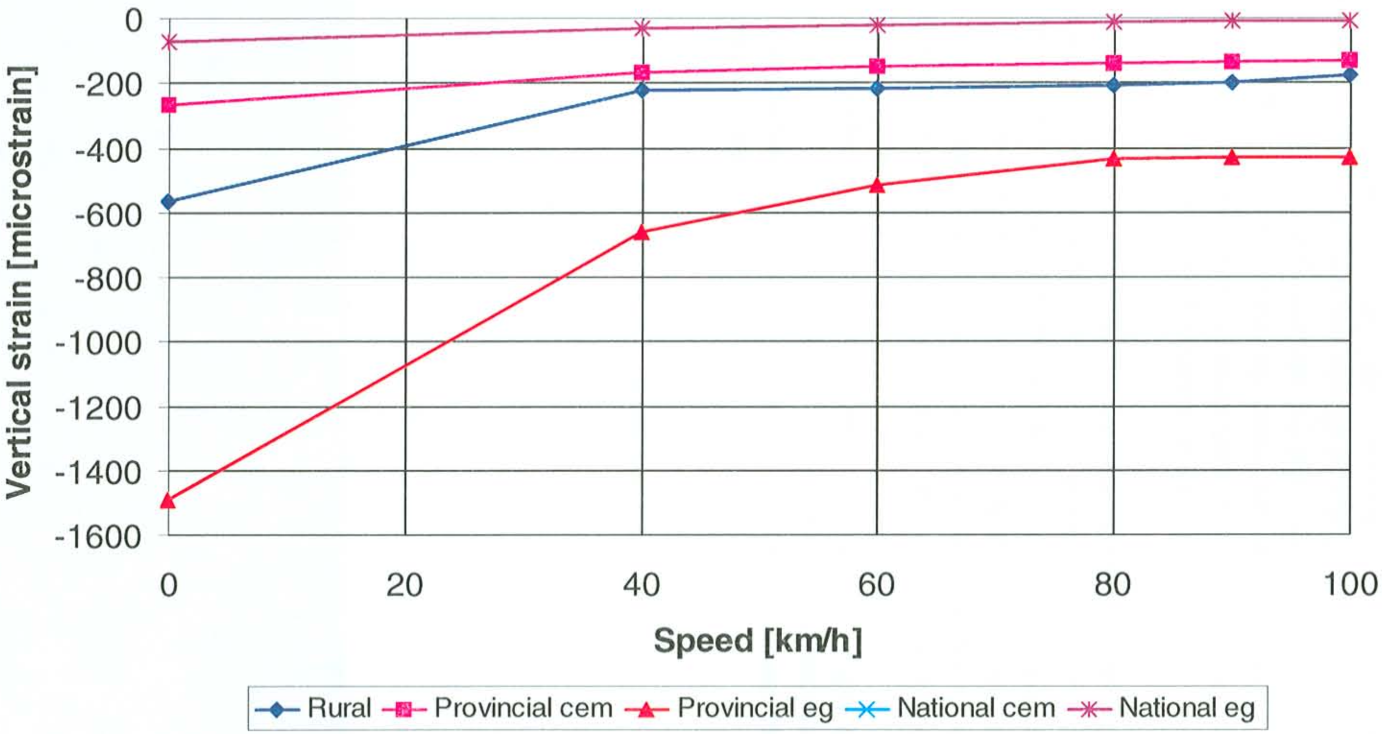


Figure 6.22: Typical vertical strain (50^{th} percentile load) against speed as calculated using MCL method.

Statistical analyses

Statistical analyses were performed on the output from the MCL analyses to determine the factors that influence each of the pavement response parameters.

The first analysis was performed to determine the effect of load *magnitude* on the vertical and horizontal stresses and strains calculated. This analysis indicated relatively good relationships (R^2 > 75 per cent) between the vertical stress and load magnitude for most of the pavements at depths of less than 200 mm (exceptions being rural pavement surface, provincial ***eg*** pavement at middle of base layer and provincial ***cem*** pavement bottom of base layer). At deeper locations the relationships decreased to R^2 -values of below 40 per cent. A similar analysis on the relationships between the horizontal stresses and the load magnitude showed higher relationships in the upper layers (between 62 and 92 per cent) and these again decreased with increased depths. The relationships obtained were mostly (28 per cent) linear, followed by double reciprocal, log x, y-reciprocal, x-reciprocal and square root x relationships.

The relationships obtained between the vertical strain and the load magnitude were not good with R^2 –values of less than 50 per cent obtained for all the relationships. The relationships obtained between the horizontal strains and the load magnitude were nominally better than those obtained for the vertical strains, although the majority of the R^2 –values were still lower than 50 per cent.

The results of these analyses indicated that pavement response (in terms of vertical and horizontal stresses) in the upper layers of the pavement is highly correlated and dependent on the load magnitude. As the mass properties of the pavement structure are also included in a finite element analysis, it is probably the effects of these overburden stresses that cause the correlation between load magnitude and stress at the deeper layers to be lower than for the upper layers in the pavement. The fact that the load is spread out over a larger area at the deeper locations may also affect this correlation. The relationships between the load magnitude and strains (vertical and horizontal) are not correlated and these strains appear not to be affected by the load magnitude to a high degree. The few higher R^2- values obtained for the correlations between horizontal strains and load magnitude were all located in the upper part (base) of the respective pavements. The relationships between R^2- values and depth into the pavement for the five pavement structures are shown in Figure 6.23.

The second analysis was performed to determine the effect of load *speed* on the vertical and horizontal stresses and strains calculated. This analysis showed relationships (R^2- values) of less than 50 per cent for most (91 per cent) of the positions investigated in each of the pavements for the stress parameters. These relationships existed for all three stress parameters investigated, at all depths. The relationships obtained were mostly (40 per cent) linear, followed by y-reciprocal, x-reciprocal and double reciprocal relationships.

Strong relationships were obtained between the load speed and both the vertical and horizontal strains, with the majority of the R^2- values being between 60 and 90 per cent. The relationships between R^2- values and depth into the pavement for the five pavement structures are shown in Figure 6.24.

These results indicated that the pavement response stress parameters (vertical, horizontal and shear stresses) investigated are not related to the load speed to a high degree. However, the strain parameters (vertical and horizontal strains) relate to the load speed to a high degree.

It thus appears as if the stress components of the pavement response correlate mainly with the load *magnitude* while the strain components correlate with the load *speed*. A possible reason is the fact that due to Newton's law indicating that an applied force will be resisted by an equal force resisting in the opposite direction, the load applied to the pavement surface (and therefore stress) must be counteracted by an equal load (stress) to keep equilibrium. However, to develop strain in a body the effect of the applied load must first act on the whole body. If the body is resisting the effects of the applied load, the time for the strain effect to take place may cause strains to correlate better with load speed than load magnitude.

The third analysis consisted of a multiple regression between the pavement response parameters (vertical, horizontal and shear stresses) and the load magnitude and load speed. These analyses showed relationships with R^2- values of more than 80 per cent for all locations shallower than 150 mm in the pavement for all pavements except the provincial ***eg*** pavement's horizontal and vertical stresses. The correlations decreased with increasing depth. The obtained equations for the relationships between pavement response parameter and load magnitude and speed all showed negative slopes of between 8 and 18 for the load magnitude parameter, and between 0,4 and 1,1 for the speed parameter. This confirms the previous observation that the effect of the load magnitude is more pronounced than that of the load speed on the pavement stresses investigated.

The multiple regression relationships between the vertical and horizontal strains and the load magnitude and load speed yielded higher R^2- values in the base layers (R^2- values of 70 to 95 per cent). It again confirmed the previous observation that the strain is mostly affected by the load speed.

Analysis of the effect of load speed on the vertical elastic deflections indicated that relationships with R^2-values of higher than 99,8 per cent exist between the load speed and the vertical deflections for all the pavement structures.

The inference from these statistical relationships between load magnitude, load speed and pavement response parameters is that the load magnitude has a dominant effect on the calculated stresses, especially in the surfacing and base layers of the pavement, while the load speed has a dominant effect on the calculated strains and deflections in the pavement.

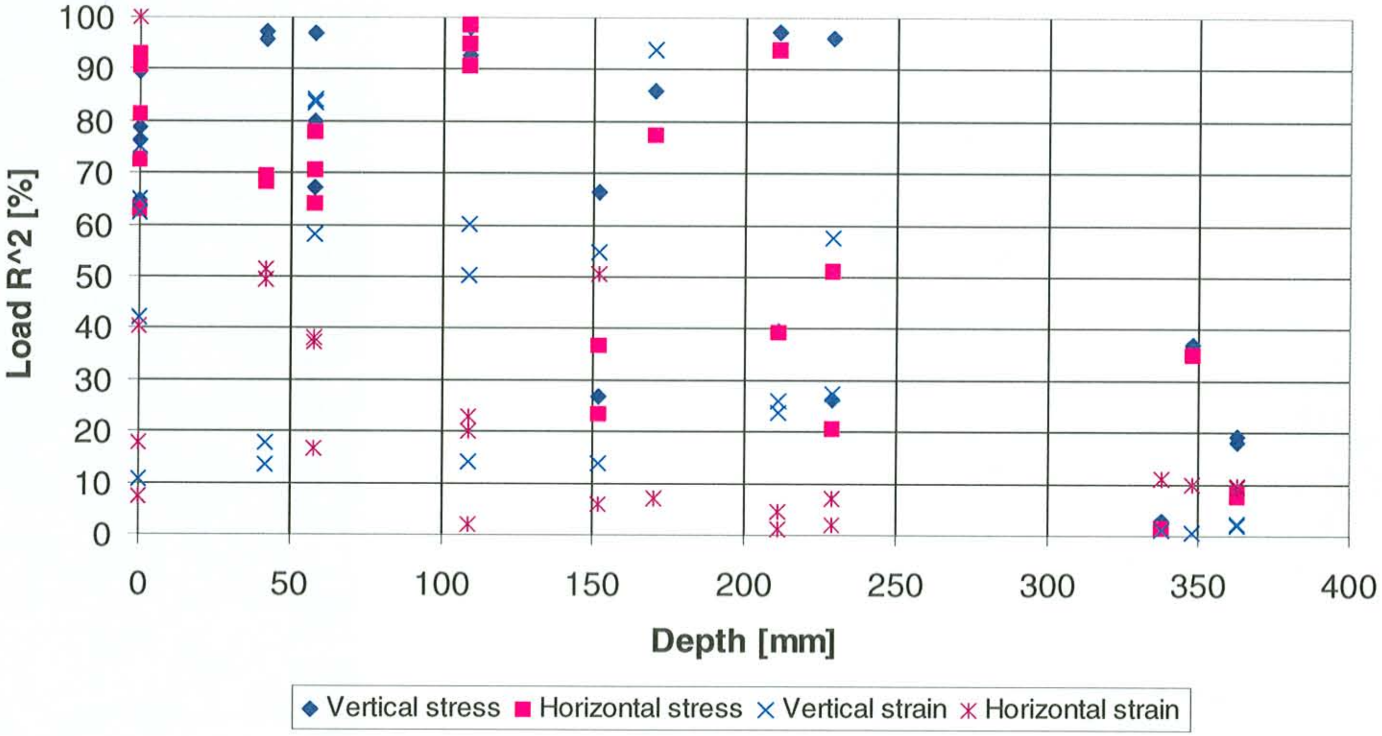


Figure 6.23: **Correlations obtained through statistical analysis of applied load magnitudes and calculated stresses.**

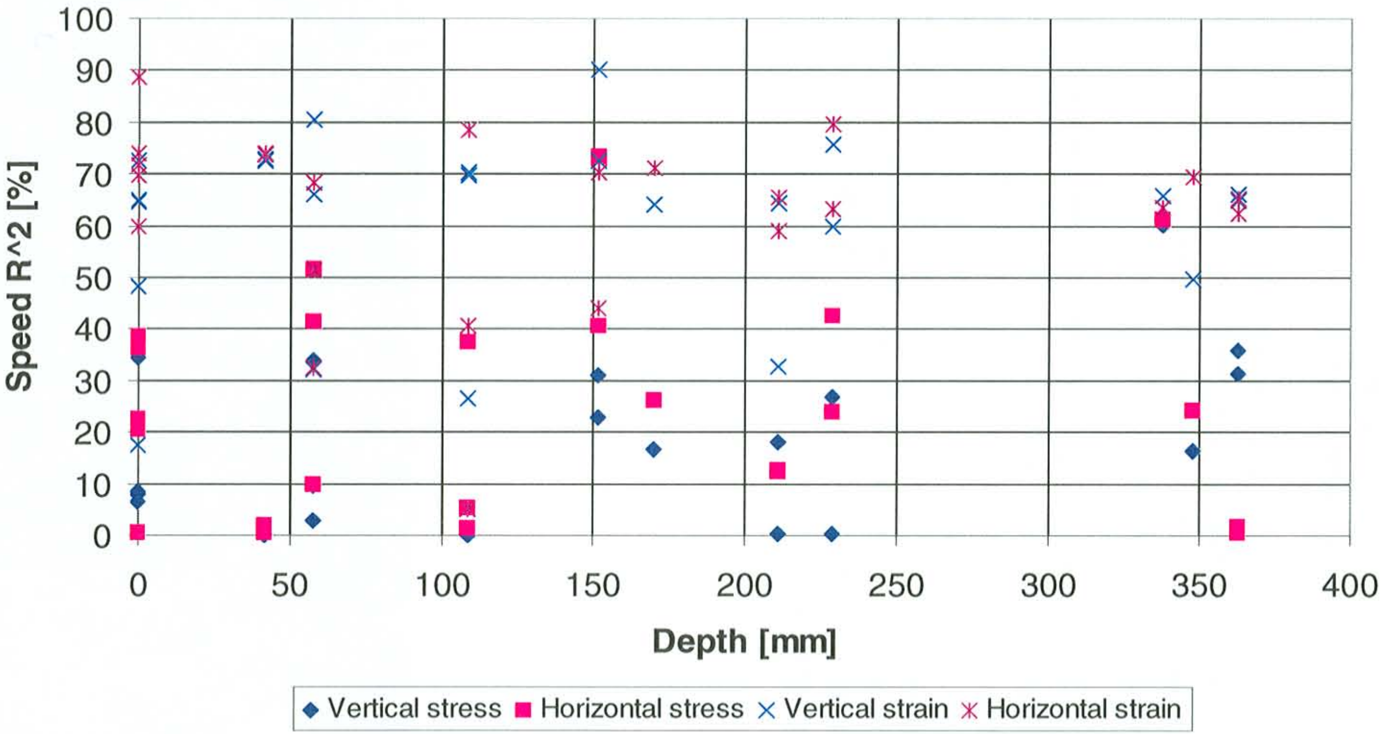


Figure 6.24: **Correlations obtained through statistical analysis of applied speed and calculated stresses.**

Effect of load frequency on pavement response parameters

It was previously (section 5.5) hypothesised that the effect of the higher frequency load variations (typical of the axle hop frequencies) have a more pronounced effect on the upper layers of the pavement structure than on the deeper levels. To test this hypothesis, analyses were performed where the same pavement structure was evaluated for the response to a load applied at a range of frequencies. The frequencies ranged from 1 Hz to 20 Hz, to extend wider than the typical scope of body bounce (around 3 Hz) and axle hop (around 18 Hz) frequencies.

It is important to distinguish between load speed and load frequency. In the previous sections the effect of load speed on pavement response parameters was investigated. Load speed is the physical horizontal speed at which the load moves along the pavement. Load frequency (which is specifically investigated in this section) indicates the rate at which the load magnitude varies with time. It is thus possible to have a tyre load with a high load speed and frequency or a low load speed and load frequency, or a combination of the two parameters.

For each of the analyses the displacements, stresses and strains were calculated for a period equal to the wavelength of the specific frequency. Typical load durations for the highway speeds used in this thesis, and a tyre patch of 300 mm, are between 0,0108 s (100 km/h) and 0,027 s (40 km/h). This represents load frequencies of between 92 and 37 Hz. It is thus realistic to expect that the calculated pavement responses for a period equal to the wavelength of the applied frequency would indicate the expected behaviour of the pavement. The first full wavelength for each load variation was used in the analyses.

To establish the effect of the load frequency on the pavement response, the ratio between the response at various depths in the pavement structure and at the surface was calculated at each of the frequencies evaluated. Using this ratio caused the response at the surface to always equal 1, and the responses at other depths to typically be less than one. These ratios provided dimensionless parameters to compare with each other. The ratios obtained for the different frequencies were then compared. The ratios were calculated using the 95th percentile load data for each of the pavements used in this thesis.

If the ratios obtained at two frequencies are equal at a specific depth, it indicates that the specific response parameter is not influenced by the load frequency at that depth. If the ratio for frequency A at a specific depth is lower than the ratio for frequency B at the same depth, then the effect of frequency A is less at that specific depth than the effect of frequency B.

In Figure 6.25 the relationship between the calculated ratios for the 1Hz (low frequency) and 20 Hz (high frequency) frequencies for the surface elastic deflection are shown. A value of greater than 1 indicates that the higher frequency affects the pavement at the specific position less than the lower frequency. The data indicates that at distances of less than 0,5 m the effect of the higher frequency loads are less pronounced than that of the low frequency loads (all at the surface) for the rural and provincial (***cem*** and ***eg***) pavements. The same is true for the national pavement (***cem*** and ***eg***) at distances less than 0,75 m from the centre of the load. Further on the effects are similar, mainly due to the very small deflection responses calculated.

In Figure 6.26 the relationship between the calculated ratios for the 1Hz (low frequency) and 20 Hz (high frequency) frequencies for the vertical compressive stress are shown. The data indicates similar trends for the rural and provincial (***cem*** and ***eg***) pavements. All these pavements are not critically affected up to a depth of 250 mm, with the lower frequency affecting the pavements more at deeper levels. The national (***cem*** and ***eg***) pavements indicate at the surface (up to 100 mm) that the higher frequency affects the pavement more. This is probably due to the relatively stiff asphalt surfacing. The general trend from the national (***cem*** and ***eg***) pavements is to be affected more by the lower frequencies at lower depths.

In Figure 6.27 the relationship between the calculated ratios for the 1Hz (low frequency) and 20 Hz (high frequency) frequencies for the horizontal compressive stress are shown. The data indicates all the pavements to be more sensitive to the higher load frequency than the lower load frequency. This is especially true for the surfacing of the national ***cem*** pavement. At deeper depths the lower frequency starts to affect the pavement again more clearly.

In Figure 6.28 the relationship between the calculated ratios for the 1Hz (low frequency) and 20 Hz (high frequency) frequencies for the compressive shear stress are shown. The data indicates that all the pavements are more sensitive to the lower load frequency, except the surfacing (asphalt) of the national pavement.

In Figure 6.29 the relationship between the calculated ratios for the 1Hz (low frequency) and 20 Hz (high frequency) frequencies for the vertical compressive strain are shown. The data indicates that all the pavements are more sensitive to the lower load frequency with an increasing sensitivity at greater depths.

In Figure 6.30 the relationship between the calculated ratios for the 1Hz (low frequency) and 20 Hz (high frequency) frequencies for the horizontal tensile strain are shown. The data indicates that all the pavements are more sensitive to the lower load frequency with an increasing sensitivity at greater depths.

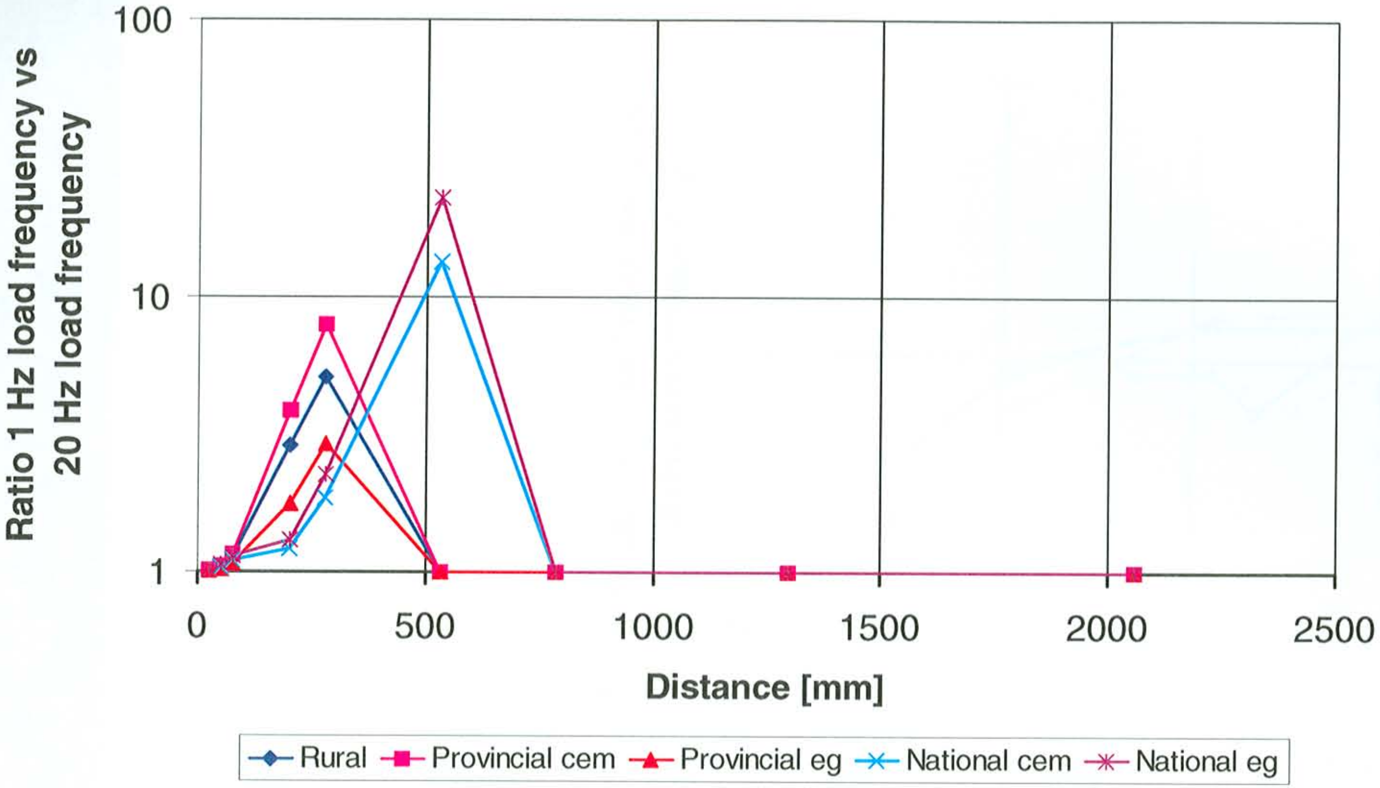


Figure 6.25: Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for elastic surface deflection.

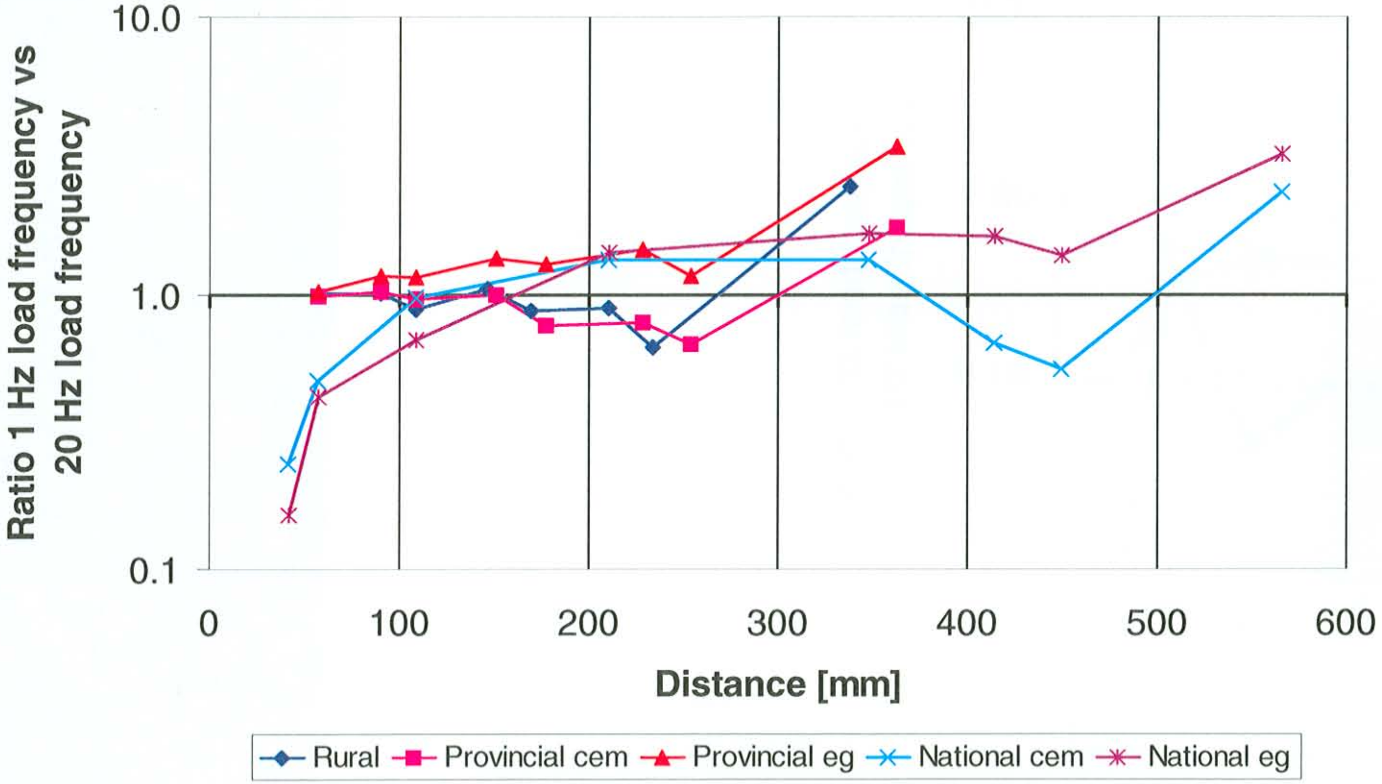


Figure 6.26: Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for compressive vertical stress.

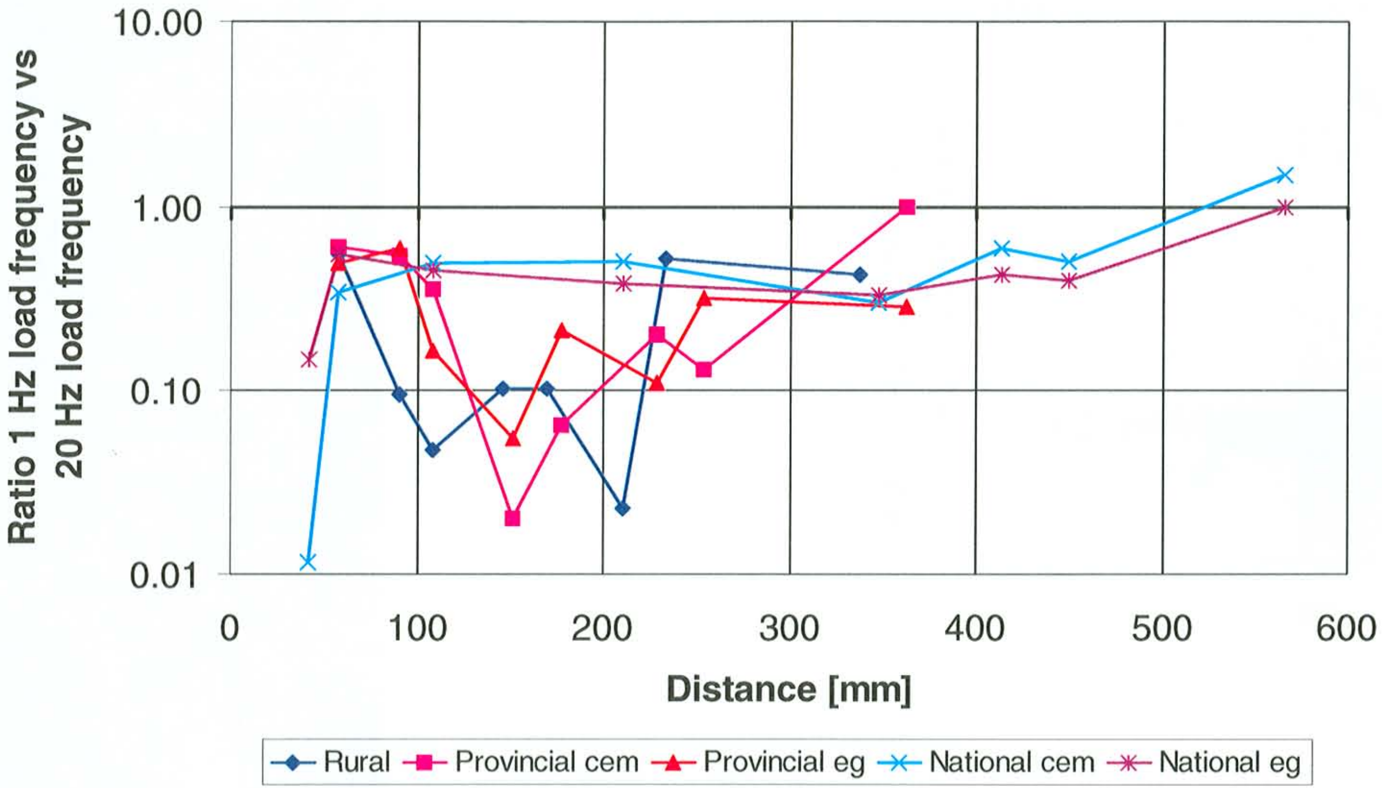


Figure 6.27: Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for compressive horizontal stress.

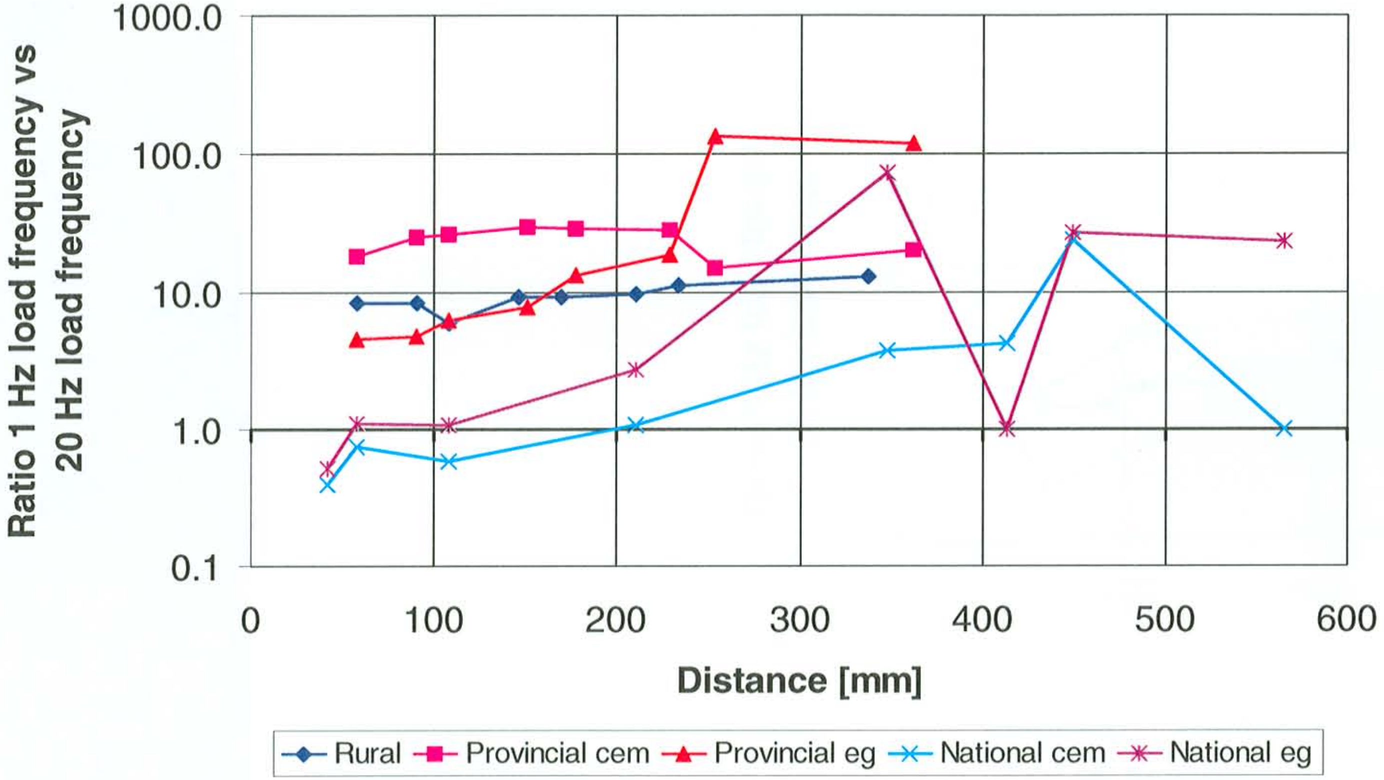


Figure 6.28 Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for compressive shear stress.

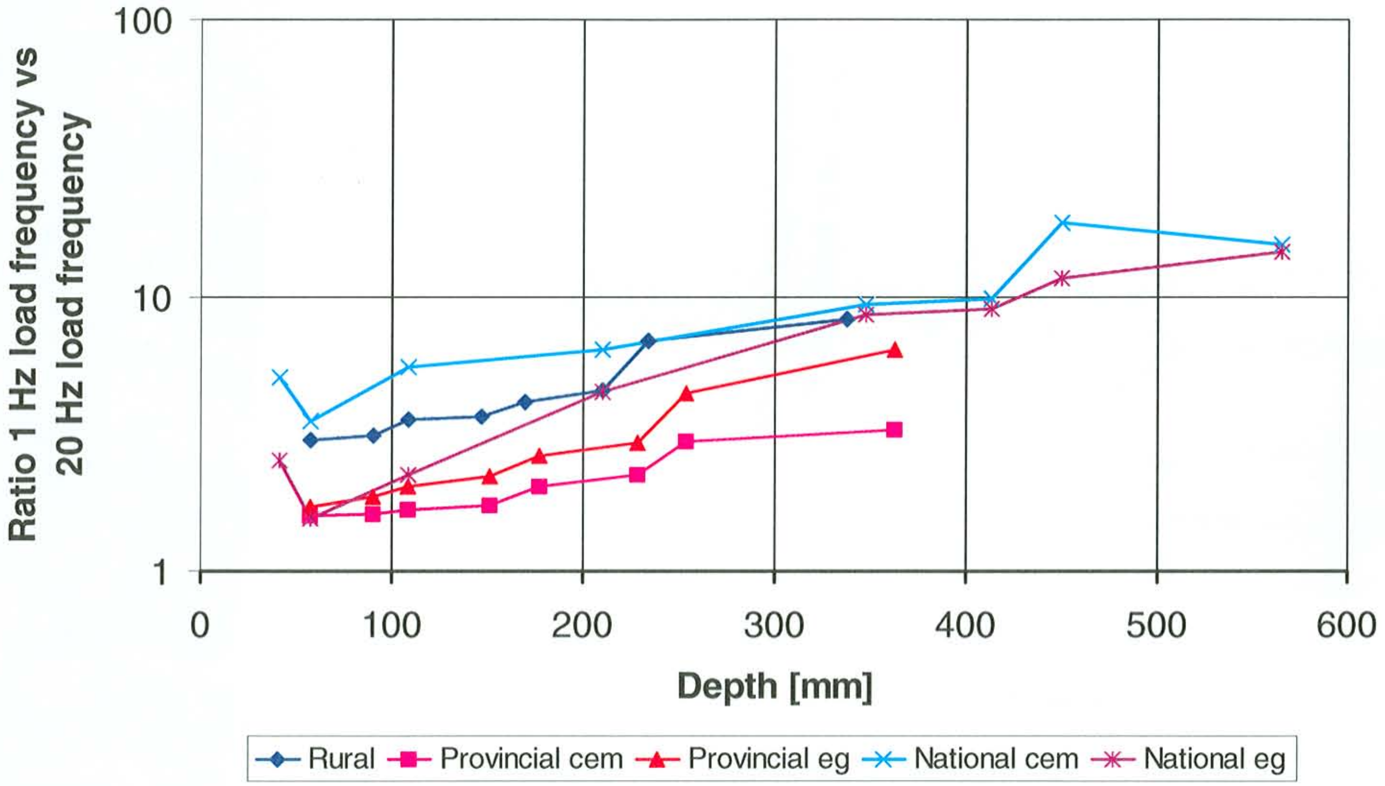


Figure 6.29: **Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for vertical compressive strain.**

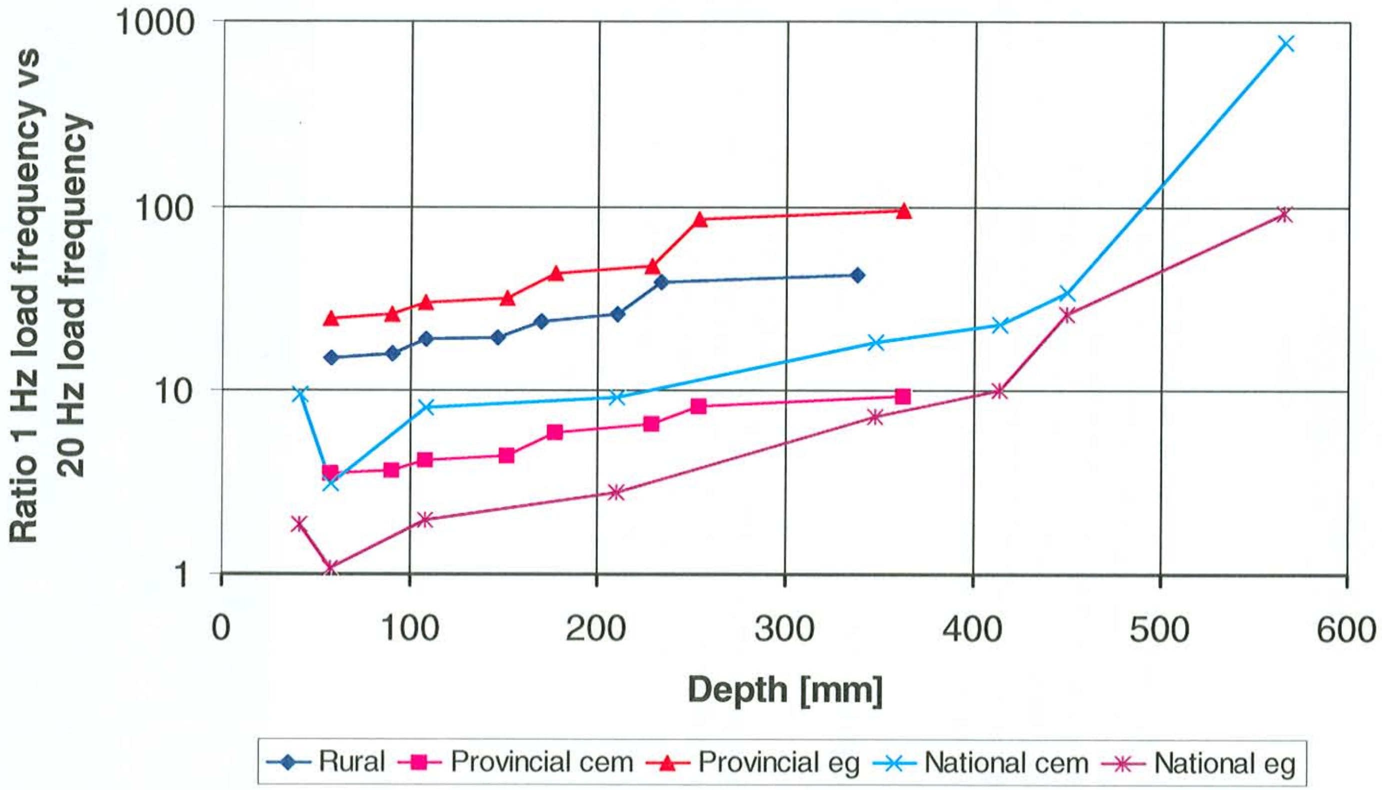


Figure 6.30: **Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for horizontal tensile strain.**

Load ratio

Under the static response analyses the ratios of the pavement response parameters at the four load levels used were the same as the load ratios themselves (Section 6.2.2). This indicates that a change in load magnitude causes a similar change in response parameter. The ratios for the pavement response parameters were also calculated for the pavement response obtained from the MCL analysis. These pavement response parameter ratios were calculated for all the parameters used in the SAMDM analysis of the specific pavement structures, as well as the maximum surface deflections.

Analysis of these load ratios calculated indicated the following:

Maximum surface deflection

The ratios of the maximum surface deflections were all lower than the corresponding load ratios. The provincial ***cem*** pavement had the closest ratio to the load ratio. The calculated ratios initially decreased between speeds of 40 km/h and 60 km/h, and remained constant thereafter. It indicates that the maximum surface deflection will increase less than the load ratio when applying the loads at speed.

Vertical stress

The vertical stress parameter showed similar pavement response ratios to the load ratios for all the pavements' upper layers (base layers). The lower layers showed lower response ratios than load ratios, indicating that the response does not increase at the same rate at the deeper locations of the pavement. The response ratios at the deeper locations decreased further with increased speeds.

Horizontal stress

The horizontal stress parameter ratios were similar to the load ratios for the upper layers (base layers). The deeper layers again showed lower response ratios than load ratios and decreases in ratio with increased speeds.

Vertical strain

The vertical strain ratios (at the top of the subgrade) were considerably lower than the load ratios for all pavements except the provincial ***cem*** pavement. All the ratios also decreased with increased speeds. This may be attributed to the depth of these layers in the pavement structure. The reason for the different behaviour of the provincial ***cem*** pavement probably lies in the thick cemented base and subbase layers of this structure. The national ***cem*** pavement also showed a higher response ratio than the remaining three structures.

Horizontal strain

The horizontal strain ratios were all similar to the load ratios although the deeper layers had slightly lower ratios than the upper layers.

In summary, it appears that most of the pavement response parameters had ratios (between their values at higher loads and at a reference load) that were similar to the ratio between the applied loads. This was especially the case for the upper parts of the pavement. Deeper locations in the pavement generally had lower response ratios than load ratios, indicating that the response parameter were lower than expected. This phenomenon is probably due to the mass inertia properties of the pavement structure. A tendency for the response ratios to decrease with increasing speeds also existed.

Pavement Response Parameter Lag

Various authors have shown a lag in response between the pavement response at different speeds and at different depths in the pavement (De Beer, 1991, 1992; Lourens and Jordaan, 1991; Mamlouk, 1987; Cebon, 1999). Mamlouk (1987) attributed this phase lag mainly to the effect of inertia and only a small extent due to the effect of damping. More pronounced phase lags were observed at higher frequencies. De Beer (1991, 1992) measured phase lag distances of between 250 mm and 400 mm between the position of the tyre and the position of maximum surface deflection, on a pavement structure similar to the national ***cem*** pavement structure used in this thesis. This compares well to phase lag distances of between 150 mm and 374 mm calculated for the national ***cem*** pavement structure in this thesis.

In order to investigate the existence of a response lag between the pavement response occurrences at different speeds, the data obtained from the MCL analyses were used.

The procedure used to calculate the lag between the pavement responses at different depths of the pavement, consisted of calculating the time between the maximum load occurrence and the maximum pavement response parameter occurrence at both the surface and the top of the subgrade of each of the pavement structures. The existence of the lag between the top of the surface and the top of the subgrade was measured in terms of the *distance* that was equivalent to the time at the load application speed for each of the analyses. This was done to normalise the increases in time lag to a standard value that would not be affected by the increase in speed. The focus for the calculations was on the maximum stress (vertical, horizontal and shear) parameters.

In Figure 6.31 the method used for the calculation is shown schematically. The distances between the position of maximum tyre load and the positions of maximum response on the surface of the pavement (at a low and a high speed) are shown together with the distances between the positions of maximum response on top of the subgrade. The figure is not to scale.

The results for the vertical, horizontal and shear stresses are shown in Figures 6.32, 6.33 and 6.34. In each of these figures the increasing distance lag due to increasing load speed is visible. The distance lags for the vertical stresses (Figure 6.32) are closely related between the five pavement types at the lower speeds (40 to 60 km/h), but becomes more spread at speeds between 80 and 100 km/h. The provincial ***cem*** pavement showed the highest distance lags at the higher speeds. This correlates with De Beer 's (1992) data showing longer phase lag distances for stiffer pavements incorporating materials with higher mass densities. The typical distance lags range between 0,08 and 0,13 m (at 40 km/h) and 0,3 and 0,45 m (at 100 km/h). A statistical correlation between the distance lags and speeds for the vertical stress indicated that an S-curve model with an R^2-value of 87,3 can be drawn between these two parameters. A statistically significant relationship exists at the 99 per cent confidence level between the two parameters.

$$\text{Distance lag vertical stress} = e^{\left(-0{,}057 - \frac{80{,}95}{\text{speed}}\right)}$$

$R^2 = 98{,}44$

Standard error = 0,06

Equation 6.1: Distance lag for vertical stress in all five pavements investigated.

The distance lags for the horizontal stresses (Figure 6.33) again indicated an increasing distance lag with increasing speed. The range of distance lags between the five pavement types increased from between 0,03 to 0,13 m (at 40 km/h) to between 0,21 and 0,39 m (at 100 km/h). The provincial ***cem*** pavement structure had the lowest distance lags with the rural and provincial ***eg*** pavement structures showing the largest distance lag values. A sharp increase in distance lag was experienced between 80 and 90 km/h. A statistical analysis of the relationship between the distance lag and speed for horizontal stress indicated that the distance lag is related to the square root of the speed with an R^2-value of 68,5. A statistically significant relationship exists at the 99 per cent confidence level between the two parameters.

$$\text{Distance lag horizontal stress} = (0{,}0686 + 0{,}00478 * \text{speed})^2$$

$R^2 = 68{,}5$

Standard error = 0,07

Equation 6.2: Distance lag for horizontal stress in all five pavements investigated.

The distance lags for the shear stresses (Figure 6.34) indicated an increased distance lag with increased speed. The distance lag values were closely spaced for speeds lower than 60 km/h (ranged between 0,09 and 0,17 (60 km/h) and 0,21 and 0,39 m (100 km/h)). At 40 km/h the national ***eg*** and provincial ***eg*** pavements had larger distance lags than the other three pavement structures. The statistical analysis showed that the distance lags were related to the natural logarithm of the speed for the shear stress data. A correlation of 0,93 was obtained and a statistically significant relationship exists at the 99 per cent confidence level between the two parameters.

$$\text{Distance lag shear stress} = -0{,}706 + 0{,}224 * \ln(\text{speed})$$

$R^2 = 86{,}2$

Standard error = 0,03

Equation 6.3: Distance lag for shear stress in all five pavements investigated.

The distance lag between the tyre (position of maximum load application) and the position of maximum pavement response parameter on the surface of the pavement was also calculated and incorporated in those distance lags shown in Figures 6.32 to 6.34.

It is important to indicate the limitations in the available data set and the parameters expected to have an influence on the distance lag values. The first limitation of the data set is that all the analyses were performed using a linear elastic material model. If viscous material models (for asphalt layers) and non-linear material models (granular layers) were used together with or instead of the linear elastic material model, the results could differ. Longer distance lags may be expected for the viscous materials.

The second limitation is the fact that only one damping coefficient and mass inertia value were used for each of the pavement structures. The current thesis does not include an investigation into the effect of these parameters specifically on the pavement response parameters, and such a sensitivity analysis was thus excluded from the thesis. It is to be expected that a change in damping coefficient and / or mass inertia for a specific pavement should affect the slope of the relationship between distance lag and speed. Specifically a higher mass inertia should cause a flatter slope (thus longer distance lags in the lower layers). A higher damping coefficient should probably not affect the distance lag as much, but would rather affect the way in which the pavement response parameter fade after the maximum value was reached. The main effect of the damping coefficient would thus be that the higher the damping coefficient the quicker the response parameter will fade out at a specific level, and the chance of the response parameter effect on a shallower level affecting the response parameter at a deeper level decreases. It is recommended that an exercise be performed to determine the relative effect of the mass inertia and damping coefficient on the slope.

The third limitation of the current study is that it focuses on only five different pavement structures with load application speeds of between 40 and 100 km/h. The effect on pavement structures with thick bituminous layers is not investigated at all. The fourth limitation of the data is that the distance lags for the strain data could not be extracted, due to the strains being calculated from the stress data obtained in the finite element analyses. As the strain data is dependent on both the vertical and horizontal stress data, the maximum strain does not necessarily occur at the same time as the maximum stress. However, it can be expected that similar distance lags exist in the strain data, as was shown by other authors (Mamlouk, 1987; Cebon, 1999).

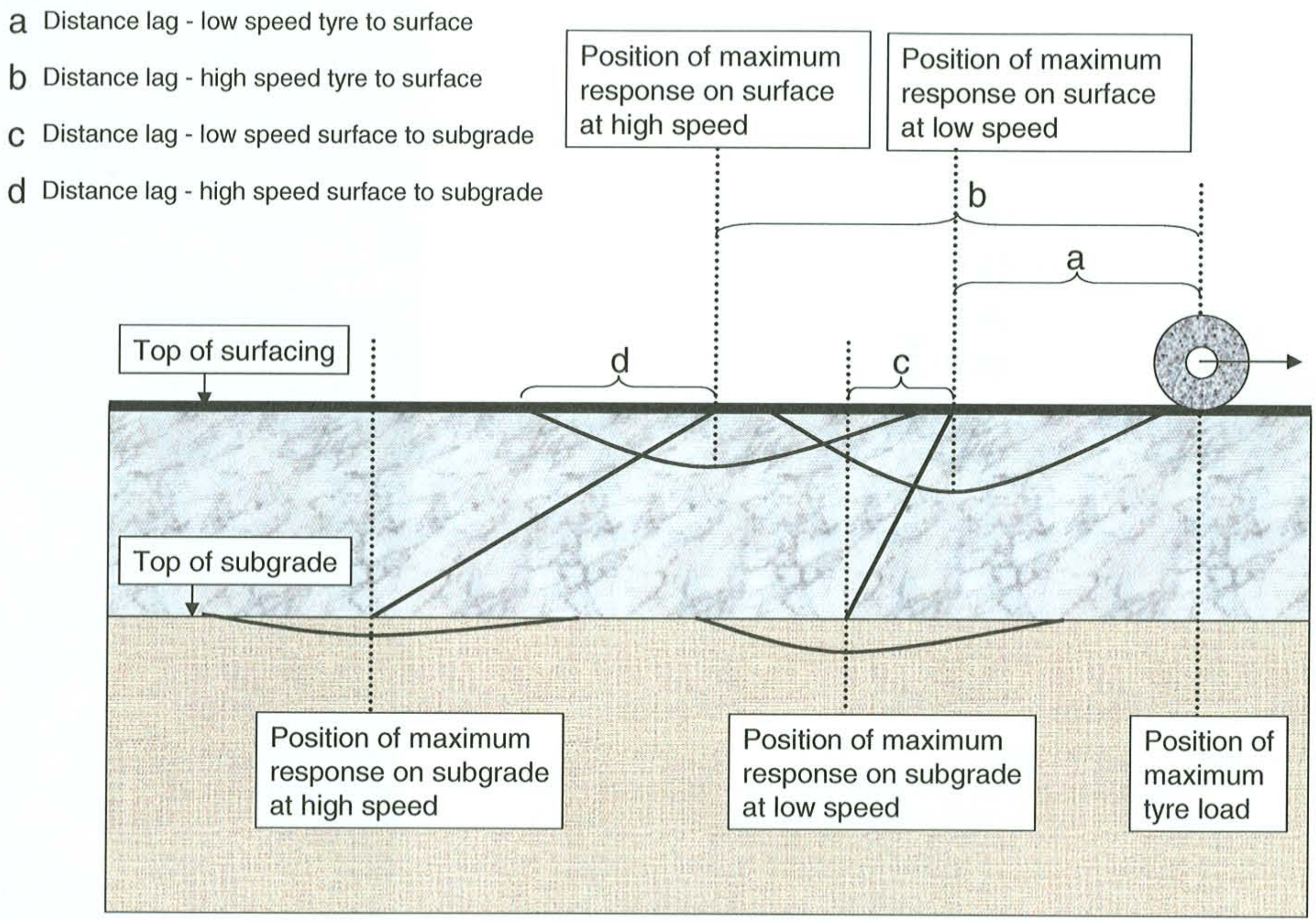


Figure 6.31: Schematic indication of distance lag between positions of maximum tyre load and maximum response on surface and subgrade of pavement structure.

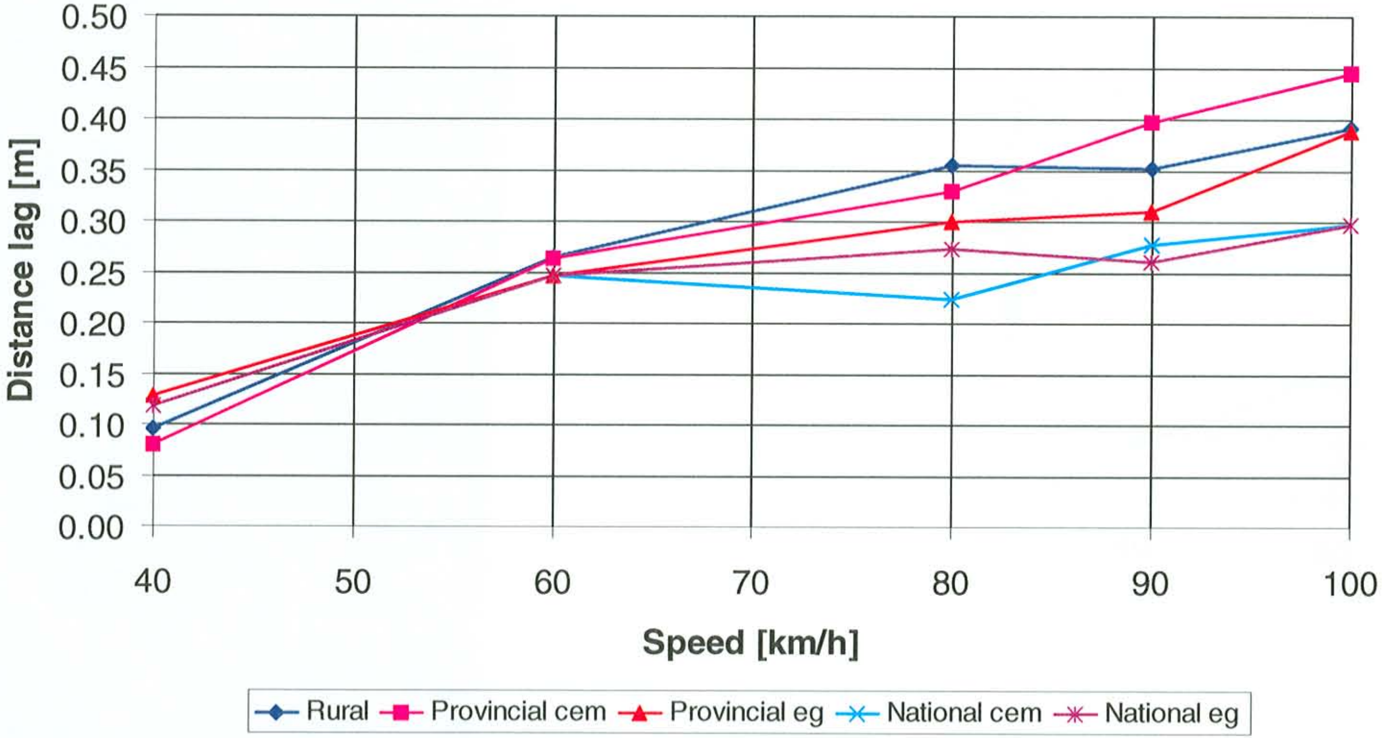


Figure 6.32: Distance lag between position of maximum vertical stress on surface of pavement and position of maximum vertical stress on top of subgrade of pavement.

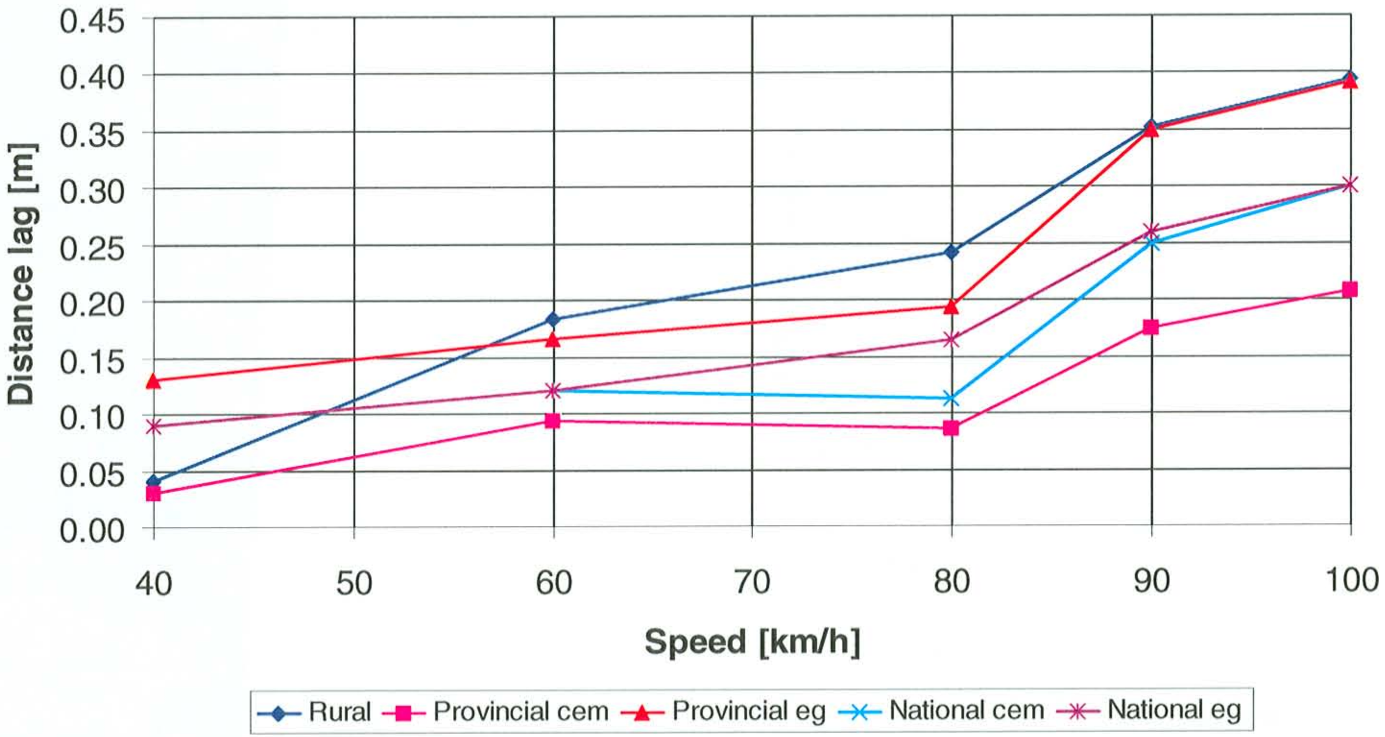


Figure 6.33: Distance lag between position of maximum horizontal stress on surface of pavement and position of maximum horizontal stress on top of subgrade of pavement.

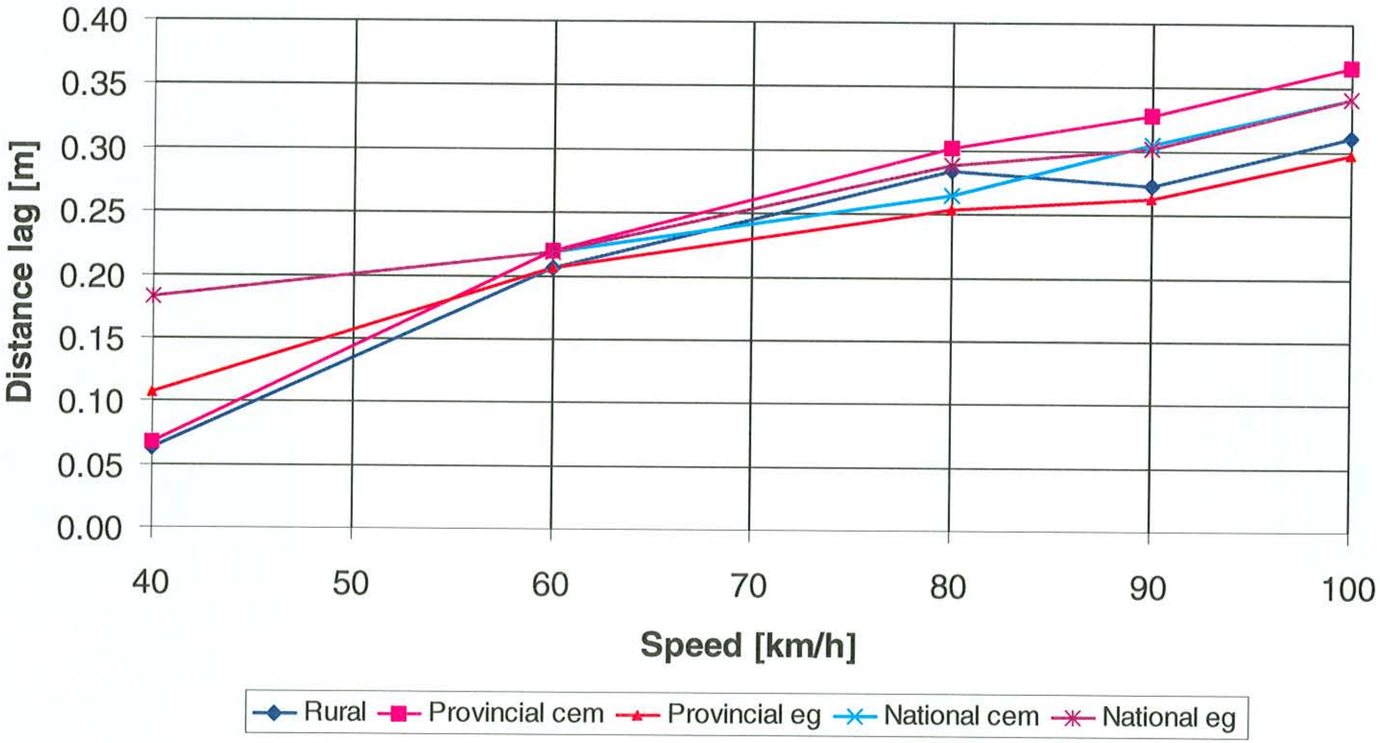


Figure 6.34: Distance lag between position of maximum shear stress on surface of pavement and position of maximum shear stress on top of subgrade of pavement.

With the stated limitations in mind, it is important to establish the effect of the distance lags shown in Figures 6.32 to 6.34. The first observation is that the position of maximum load application (the tyre) and the positions of maximum pavement response is not similar when the load is a moving load, and that this distance increases with increased speeds. A maximum distance of 0,28 m was observed between the tyre and position of maximum pavement response on the surface of the pavement. This means that in practice pavement response measurements should be done not only at the position of the tyre, but also a distance behind the tyre, especially when the load is moving at a higher speed. The reason for this distance lag is thought to be due to the mass and inertia properties of the pavement structure.

The second observation is that a distance lag also exists between the position of maximum response on the surface of the pavement structure and at positions deeper in the pavement. This distance lag also increases with increased speeds. It has been calculated to be up to 0,45 m for the conditions investigated in this thesis. The practical effect of this is that measurements of pavement response when the maximum response is occurring on the surface of the pavement structure will not observe the maximum parameter value at deeper layers in the pavement.

The third observation is that existence of this distance lag in positions of maximum stress response parameters in the pavement structure at different depths, means that the principal stress axes in the upper and lower parts of the pavement is not necessarily aligned when the load moves over the pavement. If it is assumed that the principal stress axis is vertical when the maximum vertical stress occurs at a specific position in the pavement structure, it means that a relative principal axis rotation occurs between the various layers as the load moves over a specific point in the pavement. This phenomenon is schematically shown in Figure 6.35. The effect of this rotation of principal axes is not investigated further in this thesis, although it is recommended that such an investigation be performed. An area where this effect may be important is in the analysis of falling weight deflectometer results, where the load is applied at a frequency that simulate a moving vehicle, but where the positions of maximum response are always directly below each other, and thus the principal axes is aligned at all depths in the pavement.

In summary it can be stated that the positions of maximum load application and maximum stress response at the different depths in the pavement are not similar when the load is moving, and that the distance between these positions increases with increased load application speeds. The effect of this is that the principal stress axes at different depths in a pavement are not aligned when a load moves over the pavement structure.

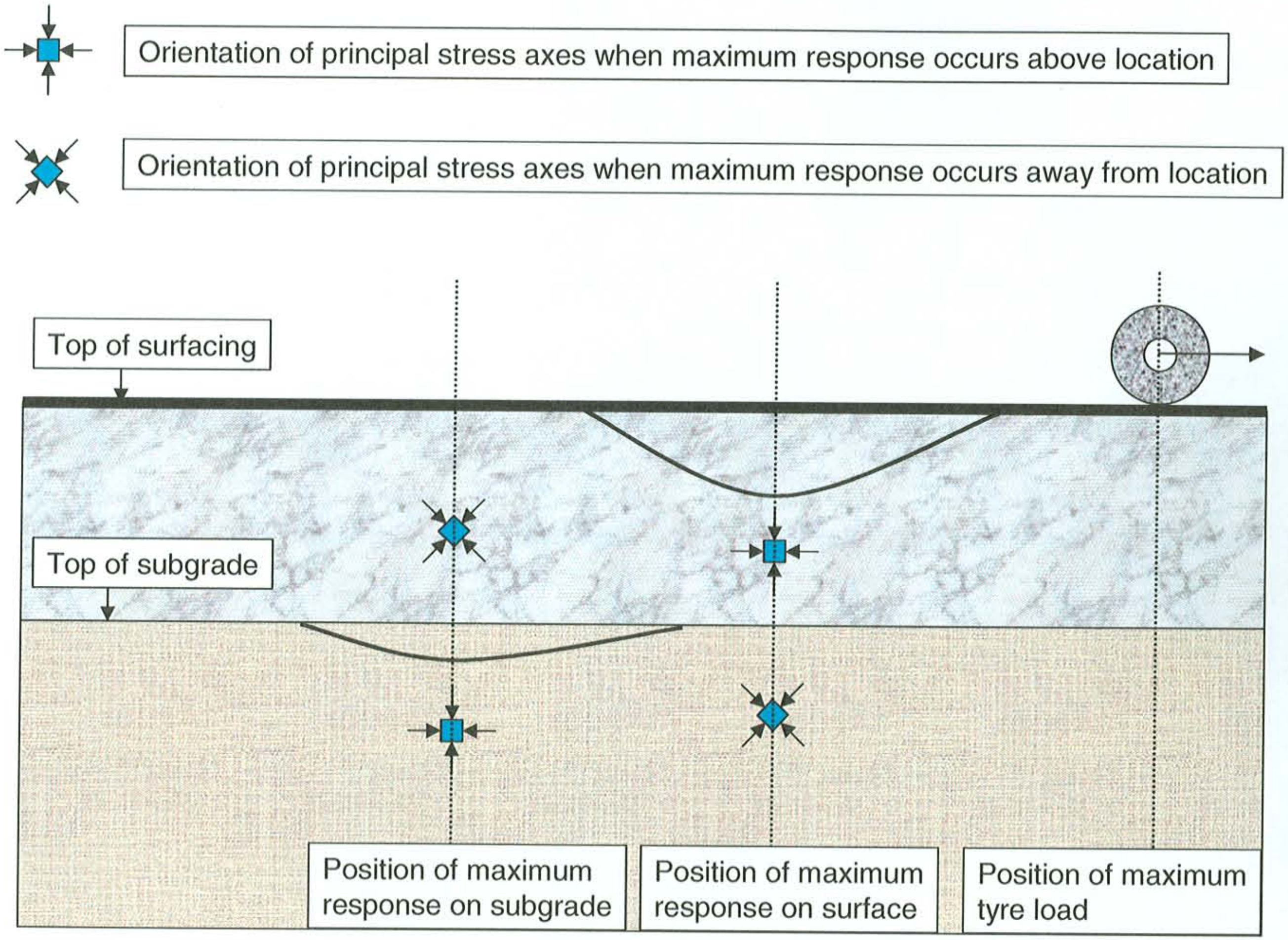


Figure 6.35: **Schematic indication of the relative orientations of principal stress axes due to distance lag in position of maximum response at different depths in the pavement structure.**

6.3.3. Expected pavement lives

The expected pavement lives using the responses from the transient analyses were calculated using the South African Mechanistic Design Method (SAMDM) transfer functions and the pavement response parameters obtained from the two transient methods.

Wolff and De Beer (1993) developed an elasto-plastic analysis method by which the development of plastic strains in the pavement can be accounted for. However, these transfer functions are based on non-linear material models. Wolff and De Beer indicated that a direct relationship does not exist between the linear and non-linear solution of the bulk stress (the main parameter used in their transfer function). As the analyses in this thesis were all performed using linear elastic theory, Wolff's elasto-plastic transfer functions can thus not be used to evaluate the residual stresses in the pavement. It is appreciated that the development of residual stresses and plastic deformation in a pavement due to repetitive tyre load applications will be of importance in analysing the pavement performance, but due to the linear elastic material models used in this thesis, it falls outside the scope of the thesis.

MCL analysis

The stresses, strains and deflections discussed in Section 6.3.2 were used to calculate the expected pavement lives for each of the different load scenarios, using the SAMDM transfer functions. A summary of the critical lives in each pavement structure is shown in Table 6.11. The most critical lives were calculated at a speed of 40 km/h. The expected lives calculated using static axi-symmetric response data are also shown in Table 6.11.

When these expected lives are compared with the expected lives indicated in the design catalogue (TRH4) for the specific pavement structures, all the pavement classes are higher than the TRH4 catalogue classes by factors 1E19 (rural), 1E13 (provincial) and 1E17 (national). This is mainly caused by the high expected lives during the equivalent granular phases of the national and provincial pavements and the whole life of the rural pavement.

The static data resulted in expected pavement lives that were closer to realistic values, especially for the provincial pavement structure. The reason for the rural and national pavement structures to be as high lies in the granular layers that are present in these two pavement structures. The Factor of Safety method is used to calculate the expected lives for these layers. This method makes use of the vertical and horizontal stresses in the middle of the pavement structure. The transient analysis resulted in compressive horizontal stresses being calculated where tensile horizontal stresses were calculated using the static response method (see Section 6.2.3). Where only the transfer functions for cemented layers were used (provincial pavement cemented phase) and no FoS method or stresses were used in the calculation, the calculated expected life is closer to that calculated using the static response method (36 per cent difference).

The reason for the higher than expected lives for the responses obtained at speed, can be found in the usage of the pavement response parameters obtained at speed together with transfer functions that were developed on pavement response at creep speeds and customised for pavement response at static conditions. The effects of speed on the parameters used in the transfer functions are discussed in detail in Sections 6.4 and 6.5.

Using the SAMDM static transfer functions will cause both the strain-based calculations and the stress-based calculations to be overestimating the lives of the pavement due to the effect of load speed and pavement mass inertia on the responses calculated.

If a reliable relationship is found between the pavement response parameters at different speeds it is possible to adapt the existing transfer functions for use with pavement response parameters obtained at speed. More discussion on this topic follows in Section 6.5.

Table 6.11: Critical expected pavement lives based on axi-symmetric finite element transient response analysis and SAMDM transfer functions.

Pavement structure (design traffic class)	Critical layer	Average expected life for most critical layer [million E80s] (traffic class)	Average total expected life [million E80s] (traffic class)	Average total expected life [million E80s] STATIC DATA (traffic class)
National (ES100)	C3	4,2 (ES10)	5,93E18 (ES100+)	4,13E6 (ES100+) Critical layers C3, G1
National (equivalent granular)	Soil	1,45E12 (ES100+)		
Provincial (ES3)	C3	2,43 (ES3)	3,95E13 (ES100+)	1,87 (ES3) Critical layers C4, EG4
Provincial (equivalent granular)	EG4	3,64E13 (ES100+)		
Rural (ES0,3)	Soil	2,58E18 (ES100+)	2,58E18 (ES100+)	7,0 (ES10) Critical layers G6

The critical expected lives indicated in Table 6.9 are all calculated under the 95th percentile load, as higher loads generally cause shorter pavement lives using the SAMDM transfer functions. All the critical lives were also calculated under the lowest (40 km/h) speed. Calculated lives increased with increased speeds, although not significantly. The expected lives calculated at the higher speeds were mostly also outside the range for which the SAMDM transfer functions were developed (values of 1E8 and higher). The calculated lives were generally much higher than those calculated using the static response analysis data. A complete discussion regarding the variations between the two sets of results appears in Section 6.4.

The data indicates that the expected lives of the three pavements decreased with increased load percentiles. This is to be expected, as the stresses and strains used to calculate the expected lives from, increased with increased loads.

6.3.4. Summary of transient pavement response analyses

The transient pavement response analysis consisted of analysing the response of the five pavement structures to moving constant loads. The analyses incorporated the effects of mass inertia and damping on the pavement responses. The following inferences can be made regarding these analyses:

a. Running finite element analyses is a time-consuming process that require detailed input data and data reduction techniques not normally required for static response analyses;
b. Deflection and strain values (vertical, horizontal and shear) generally decrease with increased speeds;
c. Stress values (vertical, horizontal and shear) generally remains constant with increasing speeds;
d. Load magnitude shows good relationships with the stresses in the upper part of the pavement structure, while load speed shows good relationships with the strains in the pavement structure;
e. Higher load frequencies (axle hop range) affect calculated strains in the deeper parts of the pavement less than lower load frequencies (body bounce range);
f. Higher load frequencies affect calculated stresses in the pavement less than calculated strains;
g. Horizontal stresses are generally affected more by higher frequency loads than lower frequency loads;
h. The response parameter ratios (between values at different loads and a reference load) were lower at deeper parts of the pavement than the applied load ratios, indicating that the deeper parts of the pavement is less affected under MCL than under static loads;
i. A distance lag exists between the position of maximum load application and the positions of maximum response at the surface and lower down in the pavement;
j. This distance lag indicates that a relative principal axis rotation occurs when a load is mover over a pavement between the upper and the lower parts of the pavement and,
k. The expected pavement lives calculated using the response parameters from a MCL analysis cause higher expected lives than when doing the calculation using static load data.

6.4. Response Evaluation

6.4.1. Introduction

The objective of Chapter 6 of this thesis is to obtain an understanding of the effect of load speed and pavement mass inertia and damping on pavement response parameters. The currently used multi-layered linear elastic analysis method and two transient pavement response analysis methods were selected to investigate this.

The main differences between the two analysis methods used are the two different load definitions and the incorporation of mass inertia and damping effects into the transient response analyses. In the evaluation of the various responses the effects of load definition (static load versus moving constant load) and mass inertia and damping cannot be separated.

The first part of this chapter focused on the relationships between the calculated stresses, strains and deflections, as obtained using the static response analysis and the MCL analysis, both for static load conditions. The objective of this was to compare the results of the two sets of data if the only difference is the analysis method (i.e. analysis with and without the effects of material inertia and damping).

In the second part of the analysis the results from the static response analysis are compared with that from the MCL analysis at the various speeds. The objective was to evaluate the effect of speed on the calculated pavement response parameters.

In this, the third part of the analysis, the expected lives from the static response analysis and the MCL analysis are compared. The objective is to evaluate the effect of the pavement response parameters obtained at different speeds when using the static SAMDM transfer functions. Care must be used in this evaluation, as the transfer functions used in the SAMDM were developed using slow moving (3 km/h) Heavy Vehicle Simulator (HVS) pavement response data together with static response analyses and a multi-layered linear elastic approach. Although the material model used in the analyses in this thesis was also a linear elastic model, the effect of speed on the transfer functions, as well as the effects of mass inertia and damping as incorporated using the transient methods, are not exactly known. This limitation was also highlighted in Section 4.5.3. The expected lives are calculated based purely on load applications and environmental effects are excluded in the current analysis.

6.4.2. Static data analysis

In order to verify the pavement response parameters obtained through the use of the MCL method, an analysis was performed for each pavement with a static load condition using the MCL method. This was especially necessary to verify that parameters such as the mesh dimensions used in the transient analysis did not impact on the results obtained.

The elastic surface deflection, and the vertical and horizontal stresses and strains were compared with each other. A statistical analysis was performed to determine whether a statistically significant difference existed between the data obtained from the static response and transient (axi-symmetric) analysis. The statistical analyses indicated that a statistically significant difference did not exist between the data sets shown in Table 6.12 at the indicated confidence levels.

Based on these analyses it can be assumed that the pavement response parameters obtained using the static response analysis method and the MCL method would produce similar pavement response parameters under static conditions. The differences in pavement response parameters obtained between the two methods when the transient analysis is performed at non-static conditions can thus be attributed to the load speed and not to the finite element method used in the analyses (i.e. mesh dimensions and element sizes).

Table 6.12: **Confidence levels at which statistically significant differences do not exist between static response analysis parameters and axi-symmetric transient analysis parameters under static conditions.**

Statistical Parameter	Horizontal stress	Vertical stress	Horizontal strain	Vertical strain	Deflection
Mean	95%	95%	95%	95%	95%
Median	95%	95%	99%	95%	95%
Standard deviation	a	95%	99%	95%	95%
Distribution	95%	95%	99%	95%	95%

a - A statistically significant difference was shown to exist in the standard deviation of the horizontal stresses at all confidence levels.

6.4.3. Data comparison

The process to compare all the data from the various analysis methods involved a statistical comparison of the pavement response parameters obtained from the static response and the MCL methods. The main objective is to determine whether a difference exists between the calculated pavement response parameters from the various analysis methods. Relationships between these parameters are developed in Section 6.5. The data shown in the figures in this section are for all the load speeds but only for the 50th load percentile. The data from all the load percentiles are used in the development of relationships in Section 6.5.

The data used in the statistical analyses are shown in Figures 6.36 to 6.41. In these figures the pavement response parameters for each of the static response analysis, MCL and MDL analyses at different speeds are shown against pavement depth.

Vertical stress

The vertical stresses for all the pavements at various speeds are shown in Figure 6.36 against pavement depth. A band of values is evident, indicating that similar trends are obtained from the various analyses for the different data sets and analysis parameters. A statistical analysis of the data indicates that a statistically significant difference does not exist between the means of the various pavement parameters (from the different analysis methods) at the 95th per cent confidence level.

Horizontal stress

The horizontal stresses for all the pavements at various speeds are shown in Figure 6.37 against pavement depth. A band of values is again evident for the data. Four outliers on the figure are the horizontal stresses calculated using the static response analysis and the MCL analysis methods for the national (***cem*** and ***eg***) pavement structures at the bottom of the asphalt surfacing layer (50 mm) (also refer to Figures 6.5 and 6.13). These stresses were within the same band when calculated at all speeds. This may be attributed to the effect of the stiffer asphalt surfacing layer. However, the relative stiffness of this layer increased even further at speed when the elastic modulus was converted to a dynamic modulus using the Asphalt Institute Formulas. A statistical analysis of the horizontal stress data indicated that a significant difference did not exist between the means of the data at the 95th per cent confidence level.

Shear stress

In Figure 6.38 the shear stresses for all the pavements at various speeds are shown against depth. The values decrease with increased depth, but do not fall into a clearly defined band as for the vertical and horizontal stresses. A few outliers occur at depths of between 350 and 450 mm in the national (***cem*** and ***eg***) pavements under static conditions. A statistical analysis of the shear stress data indicated that a statistically significant difference did not exist between the means of the data at the 95th per cent confidence level.

Vertical strain

The vertical strain data from all the pavements are shown in Figure 6.39 against depth. All the speeds are included in the data. Although scatter is evident in the data, it is apparent that the data obtained from the calculations at speed are generally smaller than the data obtained from the static analyses. Static analyses showed higher vertical strain values, especially closer to the surface of the pavements. A statistical analysis of the data indicated that statistically significant differences exist between the mean values of the static data and the MCL data at the 95th per cent confidence level. The MCL data and the static data formed two clearly separate populations.

Horizontal strain

The horizontal strain data for all pavements and speeds are shown in Figure 6.40 against depth. The data obtained from the MCL analyses are smaller than those data obtained from the static load analyses. The statistical analysis again indicated that statistically significant differences exist between the mean values of the static data and the MCL data at the 95th per cent confidence level. The MCL data and the static data again formed two clearly separate populations.

Shear strain

In Figure 6.41 the shear strain data from all the pavements and obtained at all speeds are shown against pavement depth. Although a decreasing trend is visible with increasing depth, it is apparent that the static load data do not follow this trend. The statistical analysis confirmed this trend. A statistically significant difference in mean values was observed at the 95th per cent confidence level between the static response analysis and all the MCL analysis data. No statistically significant difference was observed between the mean values of the MCL data at 0, 40 and 60 km/h at the 95th per cent confidence level, and also between the data at 40, 60, 80, 90 and 100 km/h. Three distinct groups of data were thus evident in the shear strain population.

The following inferences can be made based on the evaluation of the pavement response parameters:

a. The stress data (vertical, horizontal and shear) generally shows less sensitivity to load speed than the strain data, with no statistically significant differences between the populations of the means of the stress data at the 95th per cent confidence levels;

b. The strain data (vertical, horizontal and shear) generally shows a sensitivity to load speed with statistically significant differences in the means at the 95th per cent confidence levels between the static data and the data obtained at all speeds.

6.4.4. Expected pavement lives evaluation

The expected pavement lives in this thesis were all calculated using the pavement response parameters from the three pavement response methods and the SAMDM transfer functions. These transfer functions were developed based on HVS data and with the aid of linear elastic multilayer static response analyses. Its basis is thus creep speed data (HVS data) and static response calculations.

For the static response analyses performed in this thesis (Section 6.2.3) the calculated lives are valid as the transfer functions were used with the type of input data they were developed for. However, for the transient response analyses performed in this thesis (Section 6.3.3) the input data originates from a moving load. As indicated in Section 6.3.2, the effect of load speed on the pavement response parameters is that the strains normally decrease in magnitude while the stresses remain constant or change slightly in magnitude.

Therefore, the effect of using the pavement response parameters from the transient analyses directly in the SAMDM transfer functions cause the calculated expected lives to be overestimated. The only solution to this phenomenon is to either develop new transfer functions using the transient pavement response parameters, or to relate the transient response parameters to static response parameters to enable the transfer functions to remain valid. Relationships to do this with the pavement types and traffic spectrum analysed in this thesis were developed in Section 6.5. Development of new appropriate transfer functions is not currently an option due to the cost of doing laboratory and field tests to evaluate the responses of various pavement structures to moving loads.

In general, transfer functions should not be applied using data produced under conditions outside the scope of the transfer functions' development.

6.4.5. Summary

The analysis of the data from all the pavement response analysis methods at all load and speed conditions indicated that:

a. The static response data from both the static response analysis and the MCL analysis showed similar trends and values;
b. The moving load data from the MCL analysis showed similar trends;
c. The stress data were not affected by load speed in the same order than the strain data and,
d. Use of the transfer functions developed for static conditions together with data from moving loads do not provide correct estimates of pavement life.

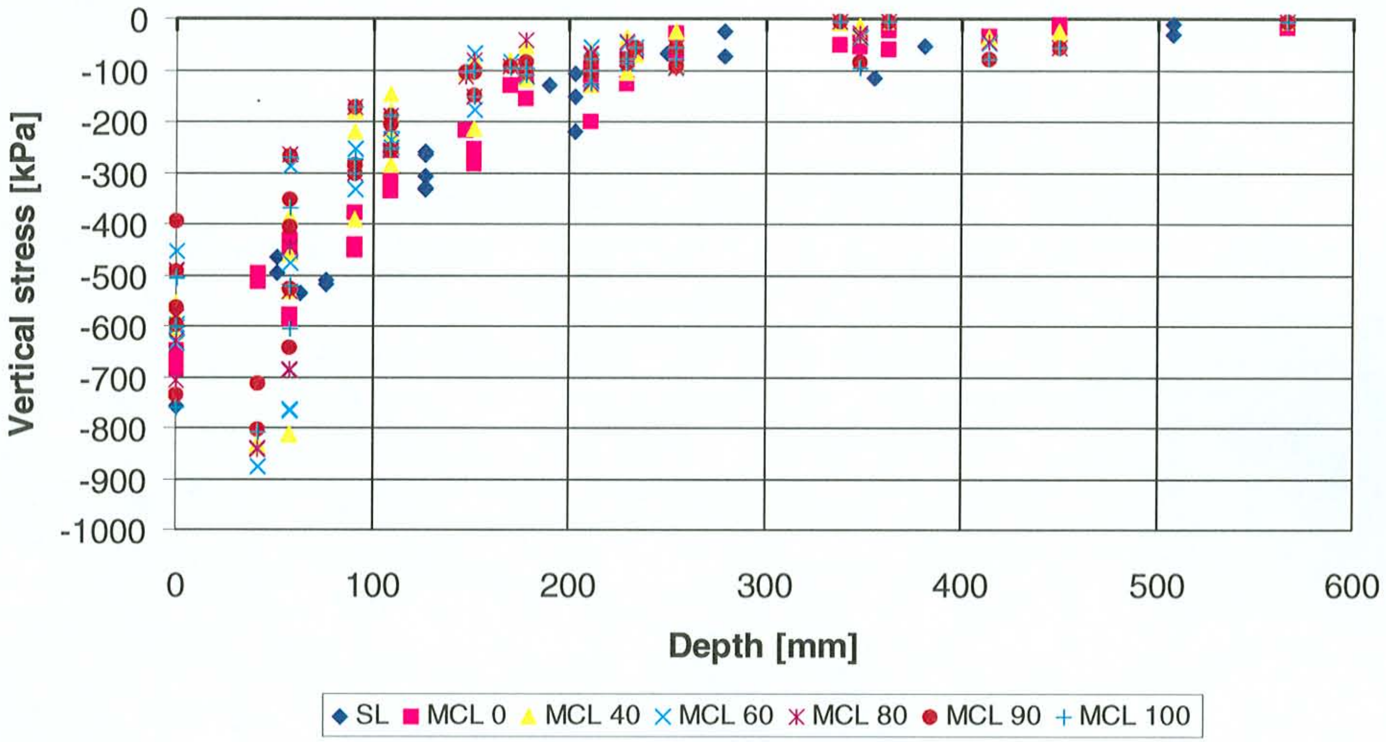


Figure 6.36: Vertical stress data at all speeds and 50th load percentile from different analysis methods.

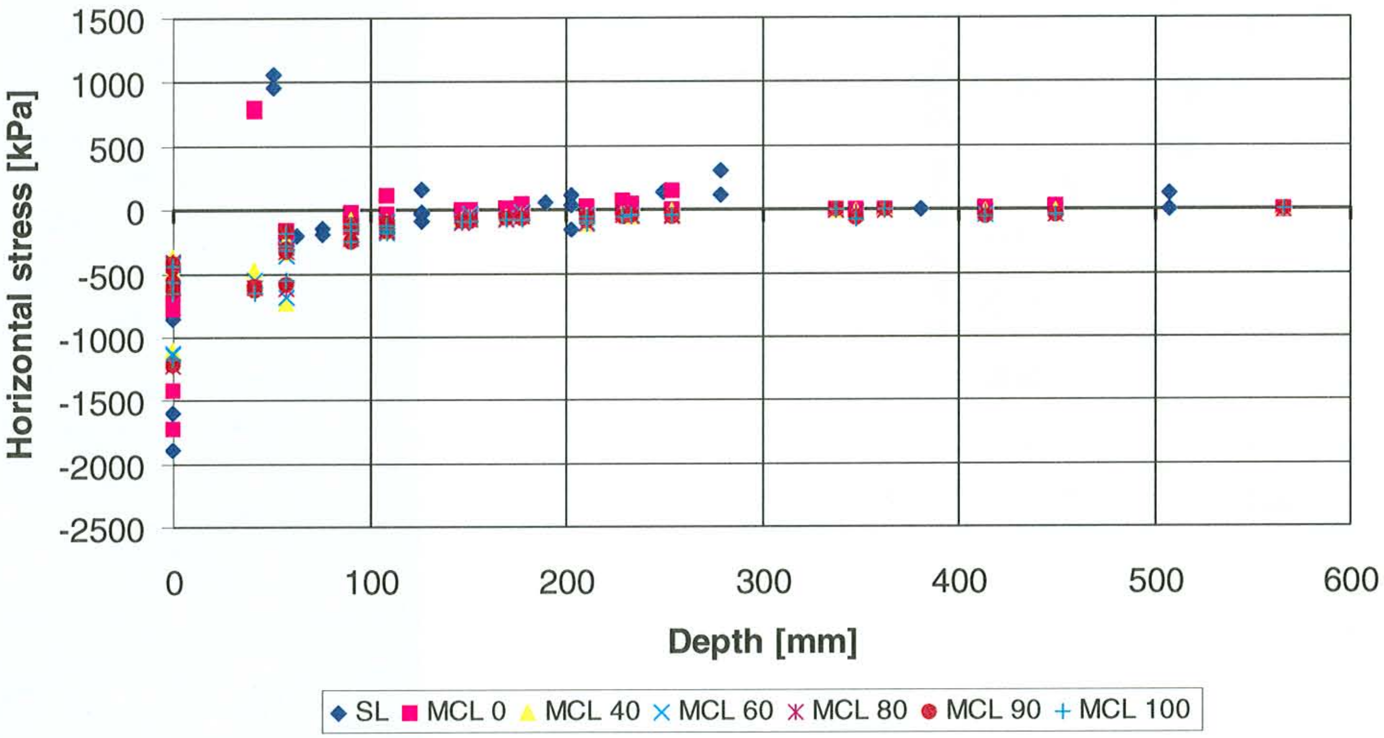


Figure 6.37: Horizontal stress data at all speeds and 50th load percentile from different analysis methods.

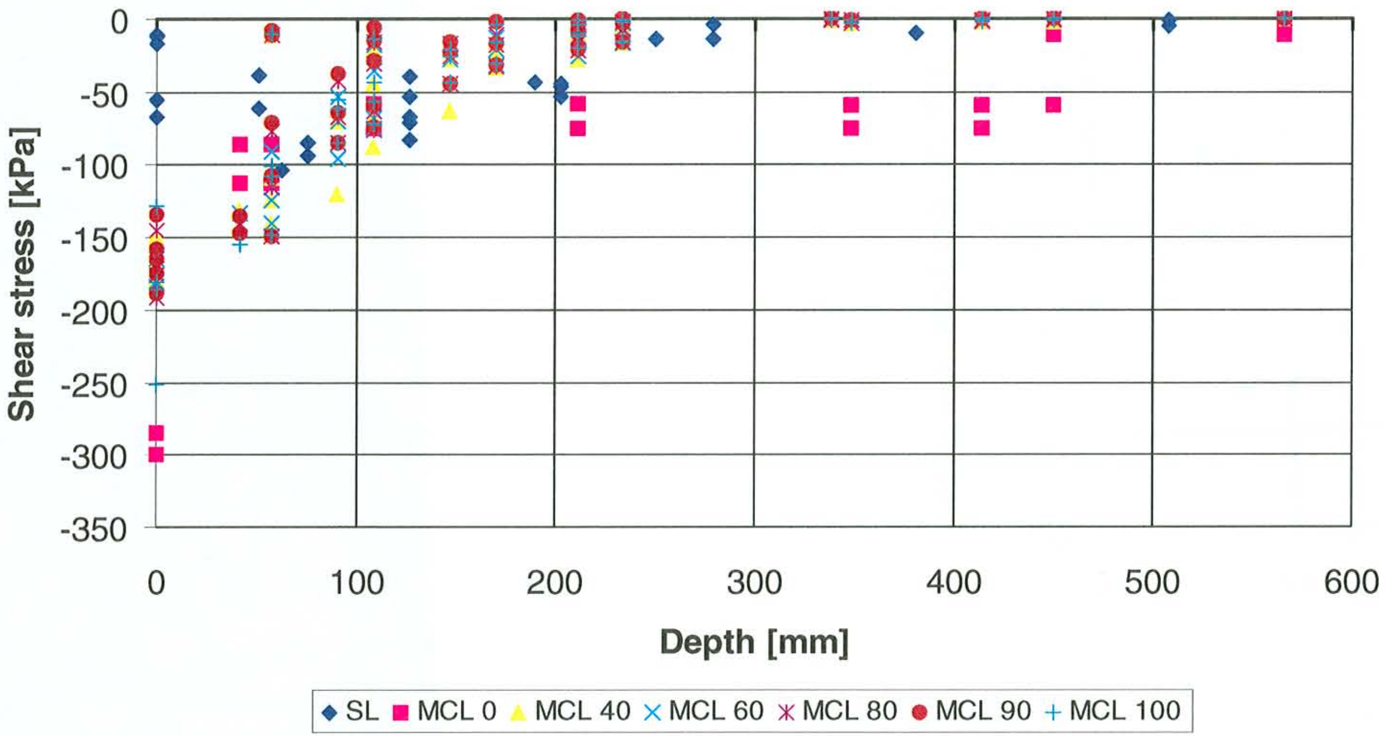


Figure 6.38: **Shear stress data at all speeds and 50th load percentile from different analysis methods.**

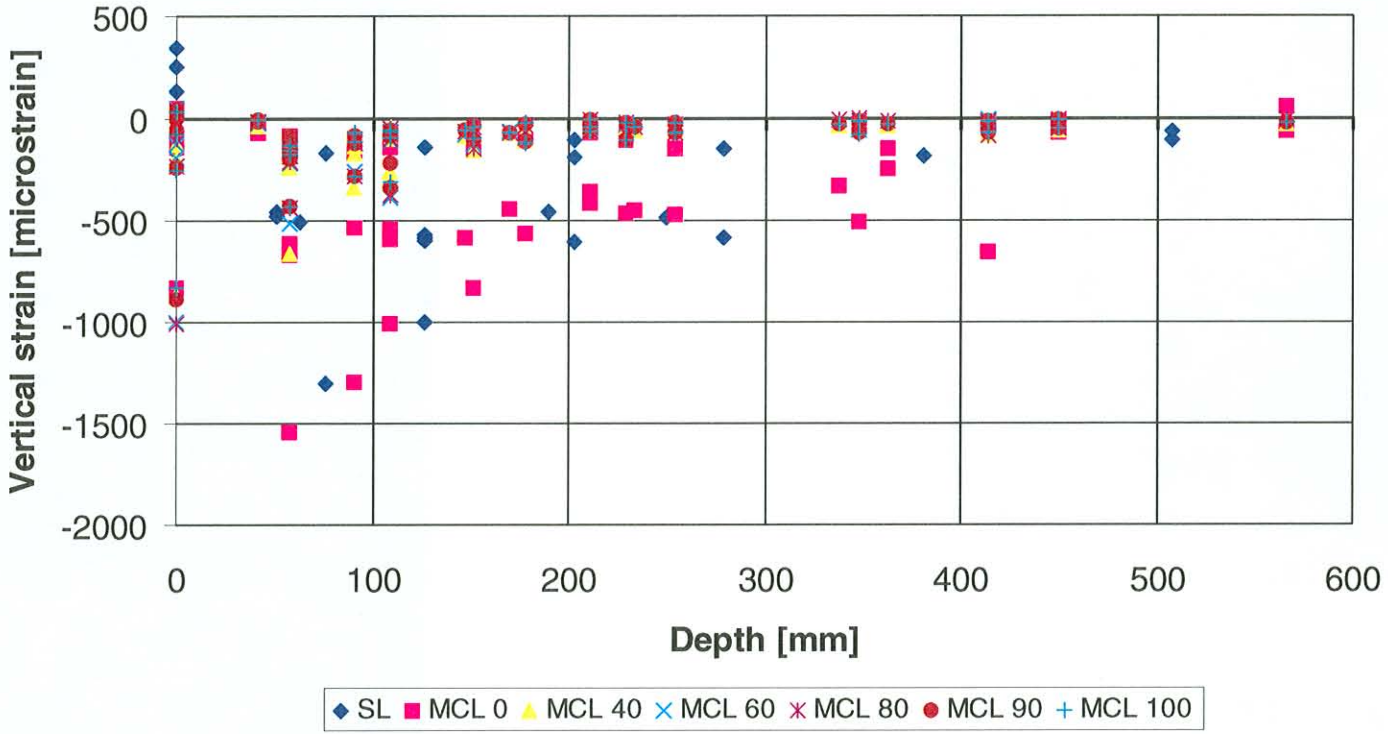


Figure 6.39: **Vertical strain data at all speeds and 50th load percentile from different analysis methods.**

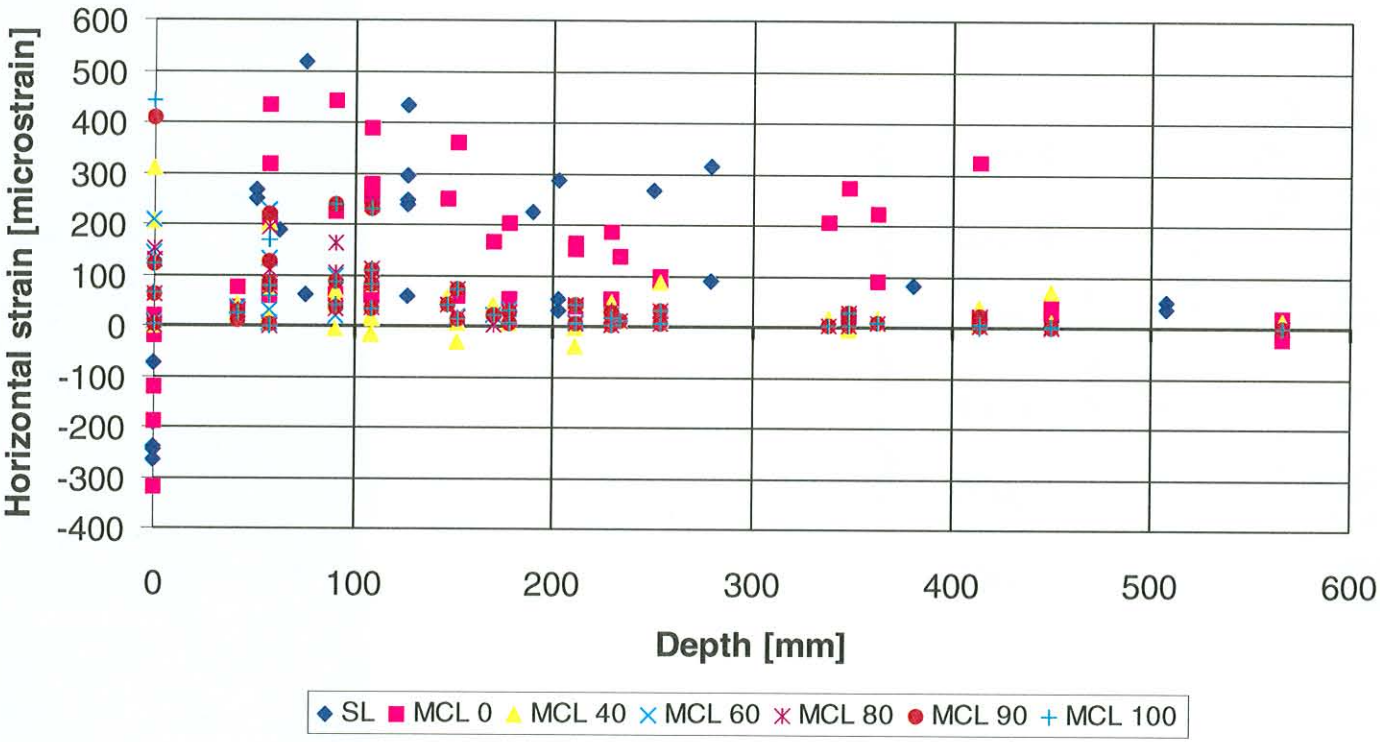


Figure 6.40: Vertical strain data at all speeds and 50th load percentile from different analysis methods.

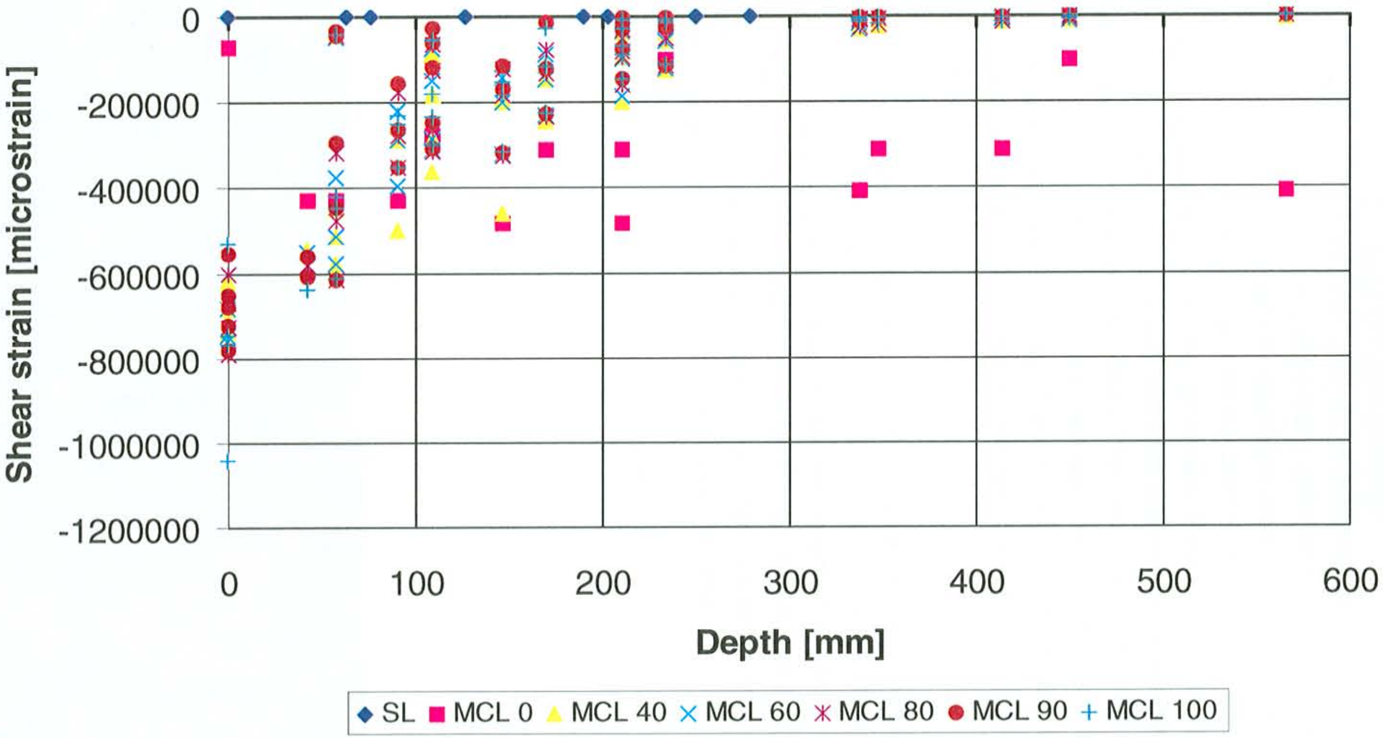


Figure 6.41: Shear strain at all speeds and 50th load percentile from different analysis methods.

6.5. Static Response Analysis with Dynamic Effects

6.5.1. Introduction

In order to provide a practical alternative to engineers for including the effects of load speed and pavement mass inertia and damping effects in their pavement life calculations without the availability of appropriate user-friendly methods to calculate the pavement responses incorporating these effects or transfer functions for these conditions, an approximate method is proposed for this purpose. This method can be used to estimate the pavement response parameters under moving loads when the static responses are available, or to convert the pavement responses calculated under moving loads to equivalent static values that may be used in the current transfer functions. The approximate method makes use of the knowledge that:

a. The deflection of the pavement reduces with increased speeds (Section 6.3.2);
b. The strains in the pavement decrease with increased speeds (Section 6.3.2);
c. The stresses in the pavement varies with increased speeds (Section 6.3.2);
d. The relationship between speed and the deflection and strain is a function of the mass inertia and damping parameters for the specific pavement type, and is not similar at all depths (Section 6.3.3).

The proposed method consists of a set of equations with which the static stresses, strains and deflections as calculated using the linear elastic static software (i.e. ELSYM5M) can be adopted for the specific speed at which the results are required. It is important to note that the proposed equations were derived based on a population of the most typical vehicles currently found in South Africa, and the responses of three typical pavement structures to these tyre loads.

6.5.2. Features and limitations of the method

The proposed method consists of a set of equations that can be applied to the calculated pavement responses (stresses, strains and deflections) obtained from the transient pavement response analysis to estimate the equivalent static response parameters. These equivalent static response parameters can then be used in the normal SAMDM transfer functions to calculate the expected life of the pavement. Conversely, the equations can be used to calculate the expected pavement response parameters at specified speeds based on the static response parameters calculated. The calculated responses would then be within the expected range of values when the calculation would be performed using a finite element-based transient response approach. The method obviously does not provide a directly related response in terms of all three the required parameters, as their respective reactions to load speed differ.

The main limitation of this method is that the factors are unique for the selected vehicle configurations, pavement structures and material properties that they were developed for. However, these equations should provide the pavement engineer with a good estimate of the expected variations in pavement response due to the effect of load speed. Further, the equations are based on the pavement response to a single tyre load, as the analyses were performed using an axi-symmetric finite element programme.

It is proposed that when the moving load response are to be used in a design or analysis, the lower 5th percentile of the speed spectrum expected on the pavement be used to keep the calculated values conservative. This is necessary as the pavement responses generally decrease in magnitude with increasing speeds, and thus slow-moving vehicles will have an greater effect on pavements than fast-moving vehicles.

6.5.3. Analysis output

The equations for the three pavement structures used in this thesis were calculated using the responses from the axi-symmetric finite element pavement response analyses. These data were used instead of the three-dimensional finite element data, as the three-dimensional data were only available for one pavement type.

The equations for the three parameters are shown in Tables 6.13 and 6.14. It is important to recognise that these factors are used with the normal static stiffness parameters, as the effect of the stiffness change due to load speed effects in (mainly) the asphalt layer is already accommodated in the factors. The convention for stresses and strains using the equations in Tables 6.13 and 6.14 is that compressive parameters are negative and tensile parameters are positive.

The equations were developed for the response parameters necessary to calculate the expected lives of the pavements using the SAMDM transfer functions (Theyse et al, 1996), as well as the maximum surface deflections. The equations focus on response parameters such as the vertical and horizontal stresses in the middle of the granular layers, the vertical strain at the top of the subgrade, and the horizontal strains at the bottom of the asphalt and cemented layers.

6.5.4. Expected pavement lives

As the equations are based on the information used in this thesis, the calculated pavement lives should agree with those calculated using the other (speed independent) pavement analyses options in this thesis.

The expected pavement lives for the three pavement structures were calculated using the responses of the pavement response calculations and the SAMDM transfer functions. These calculations were only performed for the 50th percentile load case. The expected pavement lives calculated using these equations to calculate the equivalent static pavement response parameters are shown in Table 6.15 together with the calculated expected lives for the original static response analyses.

Table 6.13: Equations for incorporating the effect of load speed into static pavement response parameters – deflection and strain.

Response parameter	Pavement type	Relationship type	a* (intercept)	b (slope)	R^2	Standard error	Position of parameter in pavement structure
Maximum surface deflection	Rural	Square root x	3,338E-01	2,737E-02	98,1	0,01100	Surface
	Provincial		1,523E-01	9,856E-03	86,4	0,01130	
	Provincial equivalent granular		4,812E-01	3,534E-02	99,3	0,00870	
	National		1,732E-01	1,730E-02	88,3	0,01800	
	National equivalent granular		2,282E-01	2,357E-02	84,9	0,02900	
Vertical strain	Rural	Square root x	-3,389E-04	-3,336E-05	75,1	0,00004	Top of subgrade
	Provincial		-1,081E-04	-1,018E-05	63,2	0,00002	
	Provincial equivalent granular		-1,715E-04	-1,747E-05	65,2	0,00003	
	National		-5,157E-05	-4,339E-06	58,9	0,00001	
	National equivalent granular		-7,699E-05	-7,259E-06	55,7	0,00002	
Horizontal strain	Provincial	Square root x	5,910E-05	2,385E-06	90,0	0,00001	Bottom of C3
	Provincial		8,314E-05	8,913E-06	93,6	0,00001	Bottom of C4
	National		3,474E-05	3,765E-06	95,9	0,00001	Bottom of C3
	National		-4,401E-4	2,808E-05	96,9	0,00001	Bottom of AC

$$\text{Equivalent moving response parameter} = (\text{Static response parameter} + b\sqrt{\text{speed}})$$

$$\text{Equivalent static response parameter} = \text{Moving response parameter} - b\sqrt{\text{speed}}$$

---

* In the equation the value of a is replaced by the Static response parameter.

Table 6.14: **Equations for incorporating the effect of load speed into static pavement response parameters – stress.**

Response parameter	Pavement type	Relationship type	c*	b (x)	a (x^2)	R^2	Standard error	Position of parameter in pavement structure
Vertical stress	Rural	2nd degree polynomial	-526,64	0,3013	0,009397	84,9	19,7	Middle G4
	Rural		-128,13	1,4407	-0,0121	93,9	4,1	Middle G6
	Provincial equivalent granular		-537,35	5,3314	-0,02725	96,8	19,1	Middle EG3
	Provincial equivalent granular		-153,04	3,6126	-0,03096	98,4	5,3	Middle EG4
	National		-327,57	4,1672	-0,02881	96,1	11,2	Middle G1
	National equivalent granular		-258,08	2,3852	-0,01733	97,3	5,6	Middle G1
	National equivalent granular		-52,92	0,4400	-0,00889	71,3	12,8	Middle EG3
Horizontal stress	Rural	2nd degree polynomial	-526,64	-0,3013	0,009397	99,1	6,1	Middle G4
	Rural		55,606	-3,476	0,0221	97,9	7,6	Middle G6
	Provincial equivalent granular		-174,42	0,3606	-0,00476	96,8	1,2	Middle EG3
	Provincial equivalent granular		21,51	-1,0011	0,001066	80,7	16,5	Middle EG4
	National		-89,44	-2,5572	0,017442	97,1	6,6	Middle G1
	National equivalent granular		-31,23	-4,1672	0,028047	96,9	10,9	Middle G1
	National equivalent granular		-5,73	-0,0012	-0,00647	75,3	14,5	Middle EG3

$$\text{Equivalent moving response parameter} = \text{static response parameter} + b * \text{speed} + a * \text{speed}^2$$

$$\text{Equivalent static response parameter} = \text{Moving response parameter} - a * \text{speed}^2 - b * \text{speed}$$

---

* In the equation the value for c is replaced by the Static response parameter.

Table 6.15: Summary of expected pavement lives based on 50th load percentile for both static response and transient response analyses and SAMDM transfer functions.

Pavement structure	**Critical layer**		**Average expected life [million E80s] (traffic class)**		**Average total expected life [million E80s] (traffic class)**	
	SL	MCL	SL	MCL	SL	MCL
National ***cem***	C3	C3	2,85 (ES3)	5,25 (ES10)	3 140 (ES100+)	297 000 (ES100+)
National ***eg***	G1	G1	285 (ES100+)	2 000 (ES100+)		
Provincial ***cem***	C4	C4	1,5 (ES3)	5,2 (ES10)	1,6 (ES3)	5,4 (ES10)
Provincial ***eg***	EG4	EG4	0,13 (ES0,3)	0,18 (ES0,3)		
Rural	G6	G6	0,14 (ES0,3)	0,15 (ES0,3)	0,14 (ES0,3)	0,15 (ES0,3)

SLA - Static load case
MCL - Moving constant load case

The new expected lives calculated for the equivalent static transient response analysis data is closer to the static response data than the values calculated using the MCL response parameters. The traffic classes for all the pavement structures are either the same or in an adjacent class. Previously, the traffic classes for the transient response analyses data were all much higher than that for the static response data. The close resemblance between the two sets of data is indicative of the close correlation between the two sets of data used for the calculation of the expected lives.

It must be stressed that the exercise using the static response data-based transfer functions to calculate expected lives using dynamic response data indicated the importance of using transfer functions only within their original boundaries. Even the intermediate method proposed in this chapter for converting dynamic response data to static response data before calculating the expected lives using the static response data-based transfer functions, does not fully take cognisance of the effect of dynamic transient loads on the transient response of the pavement structure. These relationships are based on empirical correlations between the data sets. Ideally, transfer functions should be developed with data from moving dynamic tyre loads using transient pavement response models to fully appreciate the effect of moving dynamic loads on expected pavement lives. This is, however, currently not a cost-effective and viable option in South Africa.

6.5.5. Summary of static pavement response analyses with dynamic effects

The static pavement analyses with dynamic effects option allows for the practitioner to estimate the pavement response at different speeds when the pavement response is only available at static conditions, and it allows for pavement response parameters calculated at different speeds to be converted to equivalent static values to be used together with the static SAMDM transfer functions to calculate expected pavement lives.

6.6. Observations

The following observations are made based on the information in this chapter:

All analysis methods

a. Similar trends were observed in both the static pavement response and transient pavement response analyses for all parameters at the different load levels;
b. Increased load magnitudes resulted in increased stresses, strains and deflections, as would be expected;
c. Pavement response parameters generally decreased with depth, as would be expected;

Static response analysis

a. A perfect linear relationship exists between the load magnitudes and the calculated response parameters, as would be expected;
b. The ratio between stress, strain and deflection at different load magnitudes were similar to each other and also directly proportional to the ratios between the applied loads, as would be expected;
c. The applied loads influence the expected lives of the various layers in the pavements critically, as would be expected.

Transient response analysis – moving constant loads

a. The inferences drawn around the load cases analysed using only the MCL method focus only on the transient response of the pavement to a single tyre load;
b. Running finite element analyses is a time-consuming process that requires detailed input data and data reduction techniques not normally required for static response analyses. More complicated material models affects the time required for an analysis;
c. The calculated vertical strains on top of the subgrades were similar for all pavements;
d. A statistical analysis between the pavement response parameters obtained from the static response and MCL analysis indicated that a statistically significant difference did not exist between the data sets;
e. Deflection and strain values generally decreased with increased speeds;
f. Stress values generally remained constant with increasing speeds;
g. Load magnitude shows good relationships with the stresses in the upper part of the pavement structure, while load speed shows good relationships with the strains in the pavement structure;
h. Higher load frequencies (axle hop range) affect calculated stresses in the pavement less than calculated strains;
i. Higher load frequencies (axle hop range) affect calculated strains in the deeper parts of the pavement less than lower load frequencies (body bounce range);

j. The response parameters ratios (between values at different loads and a reference load) were lower at deeper parts of the pavement than the applied load ratios, indicating that the deeper parts of the pavement is less affected under MCL than under static loads;
k. A distance lag exists between the position of maximum load application and the positions of maximum response at the surface and lower down in the pavement;
l. The expected pavement lives calculated using the response parameters from an MCL analysis are shorter than when doing the calculation using static load data;
m. Use of the transfer functions developed for static conditions together with data from moving loads do not provide correct estimates of pavement life, as would be expected, and,
n. The equations for converting static response parameters to equivalent dynamic response parameters appear to provide good relationships.

6.7. Conclusions

The following conclusions are made based on the information in this chapter:

a. A 100 per cent correlation between the pavement response parameters under static response analysis and applied loads indicates that the applied load explains the changes in these parameters fully, as would be expected from theory;
b. Load magnitude has a dominant effect on the calculated stresses using MCL analyses, especially in the surfacing and base layers of the pavement, while load speed has a dominant effect on the calculated strains and deflections in the pavement;
c. The positions of maximum load application and maximum stress response at the different depths in the pavement are not similar when the load is moving. The distance between these positions increases with increased load application speeds;
d. The reason for this distance lag is mainly due to the mass inertia properties of the pavement structure;
e. This distance lag indicates that a relative principal axis rotation occurs when a load is moved over a pavement between the upper and the lower parts of the pavement;
f. Measurements of pavement response when the maximum response is occurring on the surface of the pavement structure will not observe the maximum parameter value at deeper layers in the pavement;
g. Use of the transfer functions developed for static conditions together with data from a MCL analysis do not provide correct estimates of pavement life and,
h. The static pavement analyses with dynamic effects option allows for the practitioner to estimate the pavement response at different speeds when the pavement response is only available at static conditions, and it allows for pavement response parameters calculated at different speeds to be converted to equivalent static values to be used together with the static SAMDM transfer functions to calculate expected pavement lives.

6.8. Recommendations

The following recommendations are made based on the information in this chapter:

a. Cognisance should be taken of the fact that load magnitude and load speed affect the stresses and strains developed in a pavement differently;
b. Pavement response analysis should also be performed at speed using other material models than the linear elastic models used in this thesis;
c. The full 3-dimensional analysis of pavement response to a moving vehicle, incorporating all the axles and tyres should be performed to compare with the results from the simplified analyses performed in this thesis;
d. The proposed equations to estimate equivalent moving response parameters from static response analysis data should be used to evaluate pavement designs critically for real conditions and,
e. The effect of rotation of principal axes on the performance and behaviour of a pavement should be investigated in greater detail.

6.9. References

CEBON, D. 1999. **Handbook of vehicle-road interaction.** Lisse, Netherlands. Series: Advances in engineering, Volume 2.

DE BEER, M. 1991. **Pavement response measuring system.** Paper presented at the 2nd International Symposium on Pavement Response Monitoring Systems for Roads and Airfields, September 6-9, Hanover, New Hampshire, USA.

DE BEER, M. 1992. **Developments in the failure criteria of the South African Mechanistic Design procedure for asphalt pavements. In: Proceedings of the 7th International** Conference on Asphalt Pavements, Nottingham, UK.

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).

HUANG, Y.H. 1993. **Pavement analysis and design.** New Jersey: Prentice Hall.

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

LOURENS, J.P. and JORDAAN, G.J. 1991. **Stresses induced by dynamic loads in pavement structures: Phase 1.** Pretoria: Annual Transportation Convention.

LOURENS, J.P. 1992. **Nonlinear dynamic analysis and design of road pavements.** Pretoria: Department of Transport. (RR 90/030).

LOURENS, J.P. 1995. **Towards improved understanding of surfacing, base and tyre interaction for low-cost pavement design.** Pretoria: Department of Transport. (RR 93/559).

MAMLOUK, M.S. 1987. **Dynamic analysis of multilayered pavement structures - theory, significance and verification.** In: Sixth International Conference on Structural Design of Asphalt Pavements. (Proceedings of the 6th International Conference on Asphalt Pavements, held in Ann Arbor, Michigan, July 13 to July 17, 1987). Ann Arbor, Michigan.

OWEN, D.R.J and HINTON, E. 1980. **Finite elements in plasticity: Theory and practice.** Swansea, UK: Department of Civil Engineering, University College of Swansea, Pineridge Press Limited.

Structural design of flexible pavements for interurban and rural roads. 1996. Pretoria: Committee of Land Transport Officials (COLTO), Department of Transport. (Technical Recommendations for Highways; TRH4).

THEYSE, H.L. 2000. **Personal communication on calculations for TRH4 development.** Pretoria: CSIR, Project leader.

THEYSE, H.L, DE BEER, M. and RUST, F.C. 1996. **Overview of the South African Mechanistic Design Method.** In: Pavement design, management and performance. Washington, DC: Transportation Research Board, National Research Council (Transportation Research Record; 1539) pp 6-17.

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.

TRH 4 see Structural design of flexible pavements for interurban and rural roads.

WOLFF, H. and DE BEER, M. 1993. **Elasto-plastic modelling of granular layers.** Pretoria: Department of Transport. (RR 92/312).

7. GUIDELINES FOR PHENOMENOLOGICAL VEHICLE-PAVEMENT INTERACTION ANALYSIS

7.1 Introduction

The objective of this chapter is to summarise the information provided in this thesis into a set of guidelines to be used when vehicle-pavement interaction analyses are performed. The first focus is on the critical parameters and issues identified during the study and their effects on vehicle-pavement interaction. Secondly, guidelines for the incorporation of vehicle-pavement effects into day-to-day pavement engineering are provided. Thirdly, the issues not resolved in this thesis are highlighted, and some provisional suggestions made for addressing them.

7.2 Critical Parameters

7.2.1 Introduction

This section covers a summary of the critical parameters identified and analysed for vehicle-pavement interaction in this thesis. These parameters include vehicle components such as tyres and suspension, pavement components such as pavement roughness and the interaction between these components.

7.2.2 Vehicle components

Vehicle type, vehicle load and vehicle speed are the vehicle components analysed in this thesis (three variations of each). Components such as the tyre type, tyre inflation pressure and suspension type were not evaluated, as they were similar for all the analyses performed.

The effect of vehicle type was mainly evident in the relationships to calculate the average and Coefficient of Variation (CoV) of the tyre loads. Vehicle type occurred in these equations (Equations 5-1 and 5-2) in terms of the number of tyres on the vehicle. Furthermore, statistically significant differences were found between the tyre loads from a rigid, articulated and interlink vehicle.

The main effect of vehicle load was on the average load of the tyre load population. In Section 5.5 and Equation 5-1 it was shown that Gross Vehicle Mass (GVM) is the overriding factor affecting the average of the dynamic tyre load population. Overloading thus directly affects the tyre load population on a specific road by increasing the average tyre load.

Vehicle speed was shown in Section 5.5 and Equation 5-2 to affect the Coefficient of Variation (CoV) of the tyre load population. Higher vehicle speeds lead to higher CoV-values for the tyre load population, causing a higher percentage of peak loads in the population. Higher speeds thus increase the component of overloaded dynamic tyre loads applied to the pavement.

7.2.3 Pavement components

The nominal pavement structure and pavement surface roughness are the pavement components investigated in this thesis. Factors such as the material types, layer thicknesses and material properties were not varied in the analyses and therefore no specific conclusions are drawn around the effects of these parameters on vehicle-pavement interaction.

Each pavement structure reacted to the applied loads in a specific way. However, known behaviour such as higher elastic deflections at higher load magnitudes and lower material stiffnesses were still evident for all the pavement structures. Major differences did not occur between the response types at static and dynamic loads between the different pavements, although speed affected the magnitudes of most of the response parameters. Pavement type thus did not affect the vehicle-pavement interaction relationship significantly.

The main effect of the pavement surface roughness was shown in Section 5.5. It mainly influenced the CoV of the tyre load population as shown in Equation 5-2 (Figure 5.10). A linear increase of 1 Half-Car Roughness Index (HRI) unit was shown to cause an increase of approximately 0,03 per cent in CoV.

Lower load application frequencies (body bounce) were shown to affect the pavement response parameters deeper in the pavement structure more than higher load application frequencies (axle hop). Higher load application frequencies had more pronounced effects at the surface of the pavement and on stiffer pavement materials (i.e. asphalt and cemented layers).

7.2.4 Interaction

Vehicle-pavement interaction components investigated in this thesis are the pavement roughness induced dynamic tyre loads and their effect on the pavement structure.

The main effect of the tyre-pavement interaction was the development of dynamic tyre loads. Other authors (Sayers et al, 1986; Gillespie, 1992) have shown that the main cause for dynamic tyre loads is pavement roughness.

The main effect of tyre loads on the pavement structure is to apply stresses to the structure that have to be absorbed by the materials incorporated in the pavement structure. Analyses (Section 6.3) have shown that the stresses developed in the pavement due to the applied tyre loads are well correlated with the load magnitude (as would be expected), but less well correlated with the load speed (Section 6.3.2 and Figures 6.24 and 6.25). The strains and deflection have been shown (Section 6.3) to be well correlated with load speed but less well correlated with load magnitude. Average reductions in elastic surface deflection of 80 per cent have been calculated for an increase in speed from 0 km/h to 100 km/h.

7.2.5 Summary

Based on the information in this thesis and highlighted in this section as well as information from other sources, the phenomenon of vehicle-pavement interaction can be defined as follows:

Unevenness on pavements causes vehicles to generate dynamic tyre loads when travelling at speed over the pavements. The level of pavement roughness, type of vehicle and components of the vehicle, and the speed of the vehicle affect these tyre loads. When these loads are applied to the pavement at speed, they cause transient pavement responses that differ from the static response when static loads are applied to the pavement.

From a pavement design viewpoint the issues of pavement roughness level and transient response of the pavement materials and structure are vital in vehicle-pavement interaction.

7.3 Guidelines

7.3.1 Introduction

The objective of this section is to present the information discussed in this thesis in a guideline format, for general use by pavement engineers. It is based on the simulations, research and analyses performed in this thesis, and some duplication with recommendations and conclusions provided may exist. The chapter is structured similarly to the TRH4 (1996) document to enable practitioners to understand the changes that need to be included in a pavement design when incorporating speed and vehicle-pavement interaction effects in a pavement design. The process is structured in such a way that the practitioner does not need access to a finite element programme, but that the currently used ELSYM5M (ELSYM5M, 1995) code (or similar linear elastic multi-layered code) can be used together with the currently available South African Mechanistic Design Method (SAMDM) transfer functions (Theyse et al, 1996). The proposed method should be used in conjunction with TRH4 (1996), as sections not affected are not repeated in this guideline.

It is important to realise the limitations of the proposed process, as well as the assumptions made in the development of the equations and factors presented. These are addressed in various places in this thesis, and are repeated here for clarity. It is important to realise that all the equations and relationships presented in this thesis are empirical and should not be used outside their limits of development.

7.3.2 TRH4 structure

The standard TRH4 structure for the detailed road pavement design process is shown in Figure 7.1. The sections that are shown underlined in Figure 7.1 are those that the proposed method for incorporation of moving loads affects. The other sections can be used as described, as the moving dynamic load does not affect the parameters in these sections. The affected sections are the Pavement design (Section 3), Design traffic and pavement class (Section 4) and Structural design and pavement type selection (Section 8).

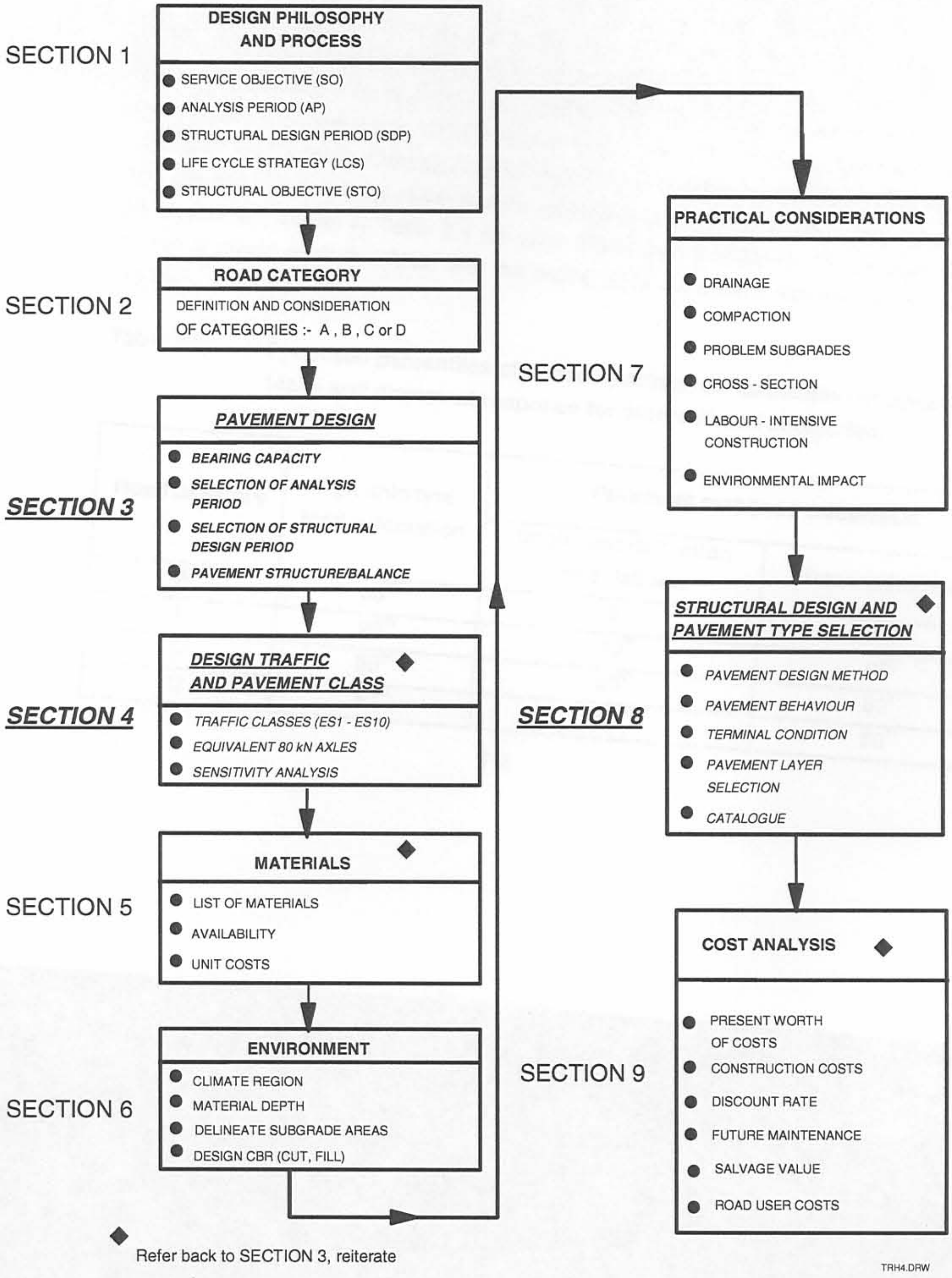


Figure 7.1: **Detailed road pavement design process (TRH4, 1996).**

Pavement design (Section 3)

Pavement design is concerned with:

- selection of the bearing capacity;
- analysis period;
- structural period, and
- pavement structural balance.

The **bearing capacity** is mainly affected by the proposed method. The main difference arises from the method by which the traffic spectrum is calculated for the pavement to be analysed. Currently the traffic spectrum consists of static tyre loads on which the population is based. The new approach entails development of a moving dynamic tyre load population in which the pavement roughness, vehicle type, vehicle load and speed play prominent roles.

It is proposed that the traffic spectrum be developed using Equations 5-1 and 5-2. Information should be gathered on the parameters needed for input in these equations. These are the Gross Vehicle Mass (GVM), average number of tyres on the vehicle population, speed population, pavement roughness assumptions and percentage of full load carried. If exact information is not available for these parameters, assumptions are needed based on current knowledge of the vehicles using the road. Preferably, this information should be collected from a traffic survey on the road.

It is recommended that the speeds at which the analysis for tyre load population be performed will be selected by monitoring the spectrum of speeds currently on the specific road or adjacent similar roads. The specific speed to be used in the calculation of Coefficient of Variation (CoV) (Equation 5-2) should be selected based on the road category. Higher speeds cause higher CoV values in the dynamic tyre load (Section 5.5). It is proposed that the higher percentiles of the speed spectrum be used to calculate the tyre loads and the pavement stress response parameters, while the lower percentiles of the speed spectrum be used to calculate the pavement strain and deflection response parameters at speed. This is to ensure that conservative estimates of the specific response parameters are used. The recommended percentiles are shown in Table 7.1 for each of the road categories. These percentiles are similar to those used in TRH4, with the higher road categories allocated smaller risks of failure.

Table 7.1: Proposed percentiles of speed spectrum for calculation of dynamic tyre loads and pavement response for different road categories.

Road category	Dynamic tyre load calculation	Pavement response calculation	
		Strain and deflection calculations	Stress calculations
A	95th	5th	95th
B	90th	10th	90th
C	80th	20th	80th
D	50th	50th	50th

Using Equations 5-1 and 5-2 incorporate the following implicit assumptions (due to the database from which they were developed):

- steel suspension;
- tyre inflation pressures at manufacturers recommended levels;
- mainly rigid, articulated and interlink vehicles on the road, and
- the speed spectrum (40 – 100 km/h), load spectrum (empty, full and 10 per cent overloaded) and roughness spectrum (HRI = 1,2; 3,1 and 5,3) as used for these developments (Sections 4.6.1 and 4.6.2).

The **structural design period** may also be affected when using dynamic tyre loads as opposed to static tyre loads. To prevent the development of undue dynamic loads due to deterioration of pavement roughness through the life of the pavement, more frequent surface improvements with the aim of correcting the pavement roughness may be incorporated in the design. This will influence the rate at which pavement roughness deteriorates and the corresponding dynamic tyre loads grow for the specific pavement.

The remainder of the information in Section 3 of TRH4 is not affected by the dynamic approach.

Design traffic and pavement class (Section 4)

Design traffic and pavement class is concerned with:

- the classification of pavements and traffic for structural design purposes;
- determining average E80/lane/day from different sources of traffic loading information;
- converting traffic loading information to design E80s;
- computing the annual average daily E80s;
- determining of future traffic loading;
- projection of traffic loading over the structural design period, and
- sensitivity analysis of determined traffic loading.

The traffic classes used in TRH4 (ES0.003 to ES100) do not change with the new approach. However, the approximate vehicles per day per lane shown in the classification may increase due to higher tyre loads generated by moving dynamic loads.

The **determination of average E80/lane/day** is done as in the current TRH4. The tyre load population generated using Equations 5-1 and 5-2 is however used as the input to these calculations. This causes the effect of the dynamic loads to be incorporated in the E80s calculated. It is important to remember that Equations 5-1 and 5-2 provide single tyre loads and that these need to be converted to single axle dual tyre loads before the calculations of equivalence are performed.

The **E80s are calculated** using the standard load equivalence equation and an appropriate relative damage exponent. The **Average Daily E80 (ADE)** is calculated by multiplying the number of dynamic axle loads in a range of load groups with appropriate equivalency factors, as currently in TRH4.

Lane distribution of traffic and **determination of future traffic loading** are done as before. However, the E80 growth rates used may be increased to cater for the deteriorating pavement roughness and concurrent increase in dynamic component of the tyre loads. No specific research has been done on this aspect, but analysis of Equations 5-1 and 5-2 indicates that for a specific tyre load population, a linear increase in number of E80s of 8 per cent for every 1 HRI decrease in pavement roughness is possible. With the presence of powerful computers and spreadsheets, it may be argued that the annual traffic loading may be calculated in a spreadsheet using different pavement roughness indicators for each analysis year. This also provides the opportunity of improving the pavement roughness indicator after a planned pavement roughness maintenance action.

Projection of traffic loading over the structural design period and **calculation of cumulative E80s** are done as currently shown in TRH4. It must be remembered that the inherent assumption is made that the vehicle population will not change significantly during the structural design period evaluated. If major changes in any of the parameters used to calculate the tyre load spectrum (Equations 5-1 and 5-2) are expected during the life of the road, a new tyre load spectrum should be calculated using the new input parameters.

Structural design and pavement type selection (Section 8)
Structural design and pavement type selection is concerned with:

- pavement design methods;
- behaviour of different pavement types;
- factors influencing pavement layer selection, and
- the catalogue design method.

The **pavement design methods** and **behaviour of different pavement types** are affected by the proposed method. The pavement design methods currently proposed in TRH4 include the South African Mechanistic Design Method (SAMDM), the Dynamic Cone Penetrometer (DCP) method, the Elasto-Plastic Design method, the California Bearing Ratio (CBR) method and the AASHTO design method. As the DCP, CBR and AASHTO methods are empirical methods they cannot be used with the dynamic tyre load populations. The Elasto-plastic design method uses non-linear elastic theory for which the equations in this thesis were not evaluated. Therefore, only the SAMDM can be used with the dynamic tyre load populations. Currently, the SAMDM is used with a linear elastic multi-layer analysis program such as ELSYM 5M (ELSYM5M, 1995) or PADS (Theyse et al, 2000).

The SAMDM is used with the selected percentile tyre load for the road category selected (i.e. 95th, 90th, 80th or 50th percentile). The stresses, strains and deflections are calculated using this tyre load and the resulting response parameters are converted to a quasi-dynamic response parameter by application of the equations shown in Tables 6.13 and 6.14. The speed used in these conversions is the percentile speed of the speed population as shown in Table 7.1.

Finally, the calculated response parameters are used with the SAMDM transfer functions for the appropriate layers to determine an estimated design life for the specific pavement. It is important to evaluate the expected pavement roughness deterioration again, as sharp deteriorations in the roughness may lead to accelerated pavement deterioration due to increases in dynamic load components.

The **economic evaluation** of the pavement is performed as currently indicated in the TRH4 manual.

7.3.3 Input data and assumptions for examples

To illustrate the process described in this section, three examples of the process are shown. In each of these examples certain assumptions are made as would normally be required to follow the process. In the first example the standard current TRH4 based analysis is performed. In the second example only the effect of tyre load population is incorporated into the design (the effect of a moving tyre load is thus neglected) while the third example also includes the effect of the moving tyre load incorporated into the example.

Two approaches can be used to show the effect of utilising the moving dynamic load spectrum in pavement design. Both approaches initially entail using a specified number of vehicles per day for which the effective static and moving dynamic load spectra are calculated. These are the traffic demands for the static and moving dynamic conditions.

The first approach then comprises calculation of the thicknesses of pavement layers to carry these traffic demands. This would ultimately lead to two pavement structures with different layer thicknesses. As this approach may lead to impractical layer thicknesses, the second approach was used in this thesis.

The second approach comprises calculation of the bearing capacity of a specific pavement structure under the two calculated traffic demands. As no changes are made to the layer thicknesses to compensate for the two load spectra, two different bearing capacities are calculated for the same pavement structure. These two bearing capacities are both valid bearing capacities for the specific pavement structure, although they resemble two points on the distribution of possible bearing capacities for the specific pavement structure. Using this approach a population of bearing capacities can be calculated for a specific pavement structure, using different assumptions regarding aspects such as the pavement roughness, vehicle speed and vehicle population. This approach adds the possibility of analysis of the risk involved in making certain assumptions and is recommended by the author. The issue of risk in pavement design is not pursued specifically in this thesis, although it is vital for a clear understanding of the real ability of a pavement structure to carry traffic.

A similar pavement structure is assumed for each of the examples and the pavement response for the calculated traffic load calculated. The nominal pavement structure analysed is shown in Figure 7.2. It consists of a 40 mm asphalt surfacing, 150 mm G2 base and a 250 mm C3 subbase. The selected layer is 500 mm G6. In TRH4 (1996) this pavement is classified as a category A road with a design traffic of 1,0 – 3,0 million E80s per lane (ES3). The pavement material input data for each of the examples are provided in Table 7.2.

Table 7.2: Pavement material input data for examples of using tyre load population and moving tyre load analyses in pavement analysis.

LAYER	PROPERTY	VALUE
Asphalt surfacing	Thickness [mm]	40
	Effective Elastic Modulus [MPa]	3 000
	Poisson's Ratio	0,4
G2 Base	Thickness [mm]	150
	Effective Elastic Modulus [MPa]	250
	Poisson's Ratio	0,3
C3 Subbase	Thickness [mm]	250
	Effective Elastic Modulus [MPa]	1 500 / 400
	Poisson's Ratio	0,3
G6 Selected	Thickness [mm]	500
	Effective Elastic Modulus [MPa]	120
	Poisson's Ratio	0,3
SG1 Subgrade	Thickness [mm]	500
	Effective Elastic Modulus [MPa]	100
	Poisson's Ratio	0,3

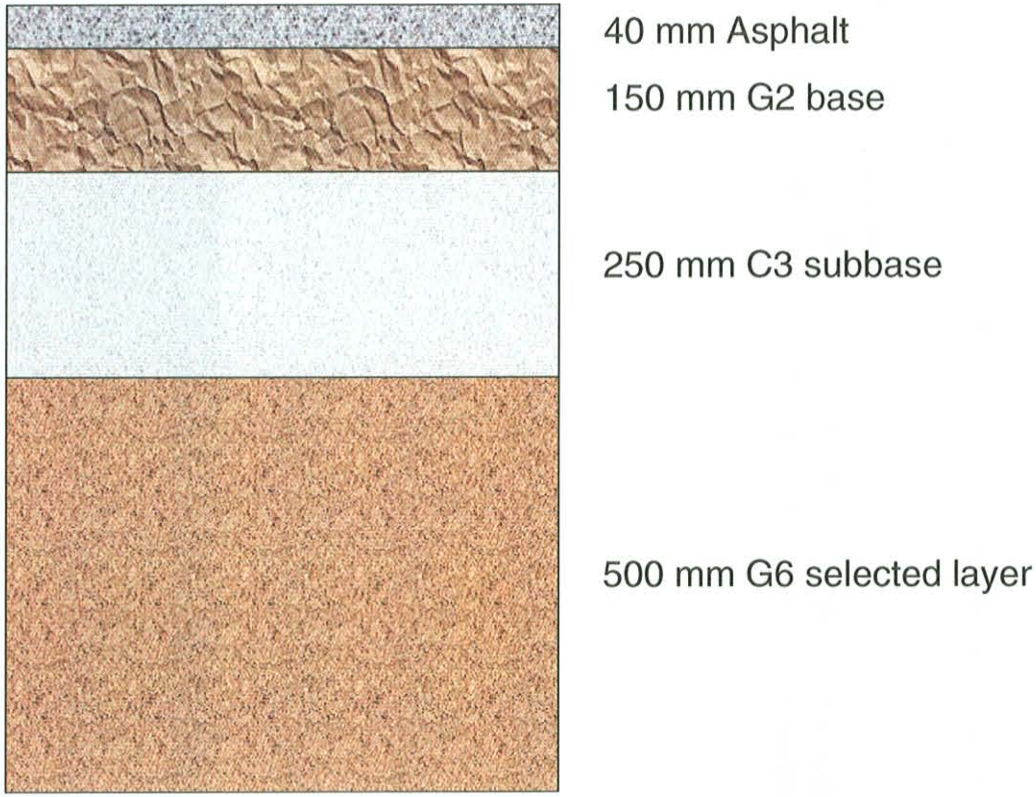


Figure 7.2: **Nominal pavement structure used for examples of vehicle-pavement analysis.**

Assumptions relevant to all three examples

The following assumptions are relevant for all three of the examples cited. Each of the assumptions is shown under the heading of the relevant section in TRH4 for easier reference.

Section 1: *Design philosophy and process.*

Analysis period = 20 years.
Structural design period = 20 years.

Section 2: *Road category.*

Road category A.

Section 3: *Pavement design.*

Analysis period = 20 years.
Structural design period = 20 years.
Design reliability = 95 per cent.

Section 4: *Design traffic.*

Load equivalence factor (n) = 3.
Two traffic lanes in both directions.
Other assumptions for design traffic are shown for each of the analyses separately.

Section 5: *Materials.*

The material characteristics data are shown in Table 7.2.

Section 6: *Environment.*

The environment is dry.
Minimum subgrade CBR = 15 per cent.
Material depth = > 1 000 mm.

Section 7: *Practical considerations.*

Adequate drainage and compaction are achieved.

Section 8: *Pavement type selection and structural design.*

The SAMDM is used for all analyses.
The PADS (Theyse et al, 2000) software is used for all calculations of response parameters.

Section 9: *Cost analysis.*

No economic analysis is performed in the examples as the comparisons between examples are based on the expected lives of the specific pavement structure.

Assumptions specific for Basic analysis

Section 4: Design traffic.

Vehicle type distribution = 1:2:1 (rigid:articulated:interlink)[1].

E80/heavy vehicle = 4,3[2]

Static axle load distribution (Figure 7.3).

Average Daily E80 (ADE) = 86,6[3].

E80 growth rate = 4 per cent.

Traffic growth factor (gx) = 1,0.

$\text{AADE}_{\text{initial}}$ = AADE = 86,6.

Cumulative factor = 11 303.

E80 total = $\text{AADE}_{\text{initial}}$ x 11 303 = 978 839 E80s.

Road category ES1.

Assumptions specific to incorporation of tyre load population and incorporation of tyre load-speed effects

The following specific assumptions are made for the remaining two analyses. Each of the assumptions are shown under the heading of the relevant section in TRH4 for easier reference:

Section 1: Design philosophy and process.

Functional service level dictates a maximum speed of 100 km/h and a typical pavement roughness level of 1,8 HRI. This information is required to determine the tyre load population from.

Life cycle strategy is selected to ensure a terminal pavement roughness of 2,7 HRI.

Section 4: Design traffic.

Average GVM = 137,2 kN (Rigid); 391,9 kN Articulated; 461,1 kN Interlink

Vehicle type distribution = 1:2:1 (rigid:articulated:interlink)

Average number of tyres per vehicle = 6 (Rigid); 22 (Articulated); 26 (Interlink).

95th percentile of the speed population = 99 km/h.

Average percentage load on vehicles = 75 per cent.

Average tyre load for tyre load population = 22,9 kN (Rigid); 17,9 kN Articulated; 17,8 kN Interlink (Equation 5-1).

Coefficient of Variation of tyre load population = 0,369% (Rigid); 0,531% Articulated; 0,571% Interlink (Equation 5-2).

Single axle load distribution (Figure 7.3)

Average Daily E80 (ADE) = 164,2 (new pavement); 170,9 (terminal condition)[4].

E80 growth rate = 4 per cent.

---

[1] The vehicle type distribution used in this example is selected purely for the sake of providing an example of the use of the method, and does not necessarily relate to a specific type of road or environment.

[2] The number of E80s per heavy vehicle for the static conditions are calculated based on the vehicle type distribution and the load levels per vehicle assumed for this example.

[3] The average daily E80 is calculated assuming 20 of the group of vehicles (1 rigid, 2 articulated and 1 interlink) to be using the road per day.

[4] The same group of vehicles as in footnote 3 have been used, but with the dynamic tyre load population from Figure 7.3 for calculating these average daily E80 values.

Traffic growth factor (gx) = 1,0.
AADE $_{\text{initial}}$ = AADE = 164,2 (new pavement); 170,9 (terminal condition).
Cumulative factor = 11 303.
E80 total = AADE $_{\text{initial}}$ x 11 303 = 1 855 952 E80s; 1 931 683 E80s (terminal condition).
Road category ES3.

Incorporation of tyre load population

The following specific assumptions are made for the analysis in this section:

Section 8: *Pavement type selection and structural design.*

The normal SAMDM is used further, as the effect of tyre load speed is not incorporated in this calculation.

Incorporation of tyre load speed effects

The following specific assumptions are made for the analysis in this section:

Section 8: *Pavement type selection and structural design.*

5th percentile speed = 23 km/h.
95th percentile speed = 99 km/h.

7.3.4 Basic analysis example

The results from the basic analysis example are shown in Table 7.3. It shows a total life of 8 million E80s or an ES10 traffic class for the pavement structure. The C3/EG4 layer was shown to the most critical layer on the structure due to its short expected life. The expected life for the asphalt surfacing (which is normally not considered as part of the total structural life in South Africa, as it is very thin relative to the remainder of the pavement structure) is only 3,2 million E80s. This is a higher class than the design class for the specific pavement structure in TRH4, but this may be attributed to the use of a dry environment (and the relevant material properties) in the analysis performed. The expected lives for the G2 base layer, G6 selected layer and in situ subgrade were relatively high, indicating that these layers are well protected.

The input data for this example were the E80-based traffic loads as shown in Section 7.3.3 (Figure 7.3). Figure 7.3 contains the cumulative distribution of tyre loads for both the static loads and the moving dynamic population as calculated using Equations 5-1 and 5-2. The stresses and strains calculated using the PADS software has been used without any modification in the SAMDM transfer functions for this example.

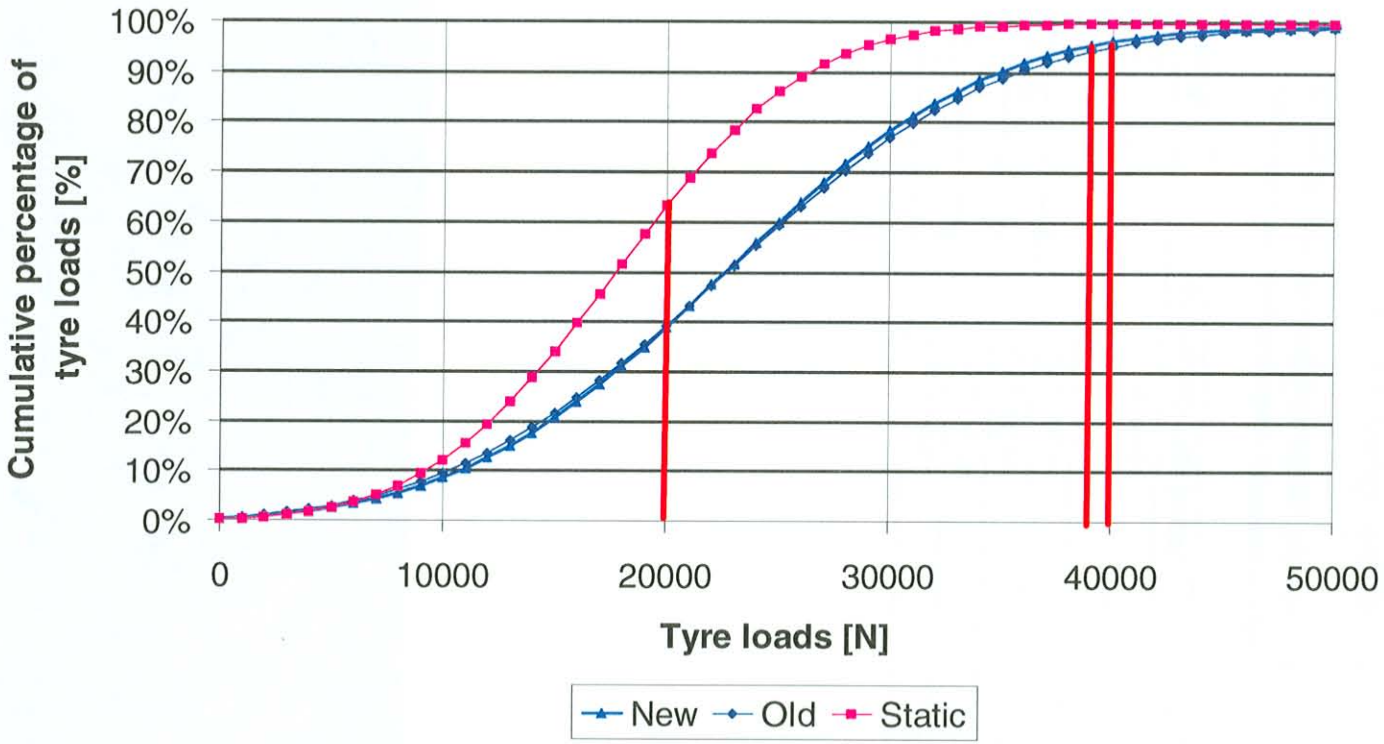


Figure 7.3: **Cumulative tyre load distributions used for examples of vehicle-pavement response analysis.**

Table 7.3: **Expected lives calculated using static E80 tyre loads and static response analysis (basic analysis).**

LAYER	EXPECTED LIFE [E80s]	TRAFFIC CLASS
Full life	7,99 million	ES10
AC	3,21 million	ES10
G2	> 100 million	ES100
C3/EG4	7,99 million	ES10
G6	> 100 million	ES100
SG1	> 100 million	ES100

7.3.5 Example incorporating tyre load population

The results from the second example are shown in Table 7.4. In this example the tyre loads generated from Equations 5-1 and 5-2 were used to calculate a population of tyre loads (Figure 7.3), and the 95th percentile of these values used as the design tyre load. The stresses and strains calculated through the PADS software has been used without any modification in the SAMDM transfer functions for this example.

The tyre loads for this example were almost double those used for the static analysis (95th percentile of tyre load population = 39 kN for initial pavement roughness and 40 kN per tyre for the terminal pavement roughness, Figure 7.3). Therefore, the expected lives calculated for the various pavement layers were less than those calculated for the static example (Table 7.3). The expected life for the whole pavement structure decreased from a class ES10 to a class ES1 (8 million to 0,6 million E80s).

The most critical layer in the pavement structure was again the C3/EG4 lightly cemented layer, while the G6 selected layer and subgrade again showed relatively high expected lives. The expected life of the G2 base layer was not as high as under static conditions.

Table 7.4: **Expected lives calculated using 95th percentile tyre load from dynamic tyre load population and static response analysis.**

LAYER	EXPECTED LIFE [E80s]	TRAFFIC CLASS
Full life	0,56 million	ES1
AC	0,27 million	ES0.3
G2	6,38 million	ES10
C3/EG4	0,56 million	ES1
G6	> 100 million	ES100
SG1	> 100 million	ES100

7.3.6 Example incorporating tyre load speed

The results from the third example are shown in Table 7.5. The same tyre loads as for example 2 were used, but the stresses and strains calculated using the SAMDM software were converted to equivalent dynamic response parameters by using the equations in Tables 6.13 and 6.14. The expected lives shown in Table 7.5 are thus compensated for the effects of the tyre load population as well as the speed.

The expected lives for the various pavement layers and the pavement as a whole decreased as opposed to the static example, but were higher than for the second example where no compensation for load speed was made. The higher tyre loads were again used as input to the example, but the stresses and strains calculated in the pavement structure were also converted to equivalent dynamic responses using the appropriate equations in Tables 6.13 and 6.14. The overall expected life for the pavement structure decreased from an ES10 traffic class to an ES3 traffic class (8 million to 2,4 million E80s).

The C3/EG4 subbase layer again showed the most critical expected life of all the layers. The G2 base layer, G6 selected and in situ subgrade layers again showed relatively high expected lives. The asphalt layer had a higher expected life than that calculated in example 2 (Table 7.4).

Table 7.5: **Expected lives calculated using 95th percentile tyre load from dynamic tyre load population and quasi-dynamic response analysis.**

LAYER	EXPECTED LIFE [E80s]	TRAFFIC CLASS
Full life	2,41 million	ES3
AC	9,71 million	ES10
G2	> 100 million	ES100
C3/EG4	2,41 million	ES3
G6	> 100 million	ES100
SG1	> 100 million	ES100

7.3.7 Comparison

In a comparison of the expected lives calculated for the three examples, the following is evident:

- The calculated life for the pavement structure as a whole is the longest under the static load (example 1) and the shortest under the moving constant load (example 2);
- The C3/EG4 subbase layer had the most critical expected life in all three analyses;
- The asphalt surfacing showed a shorter expected life under the MCL (example 2) than under the MDL (example 3). It showed the longest expected life under the static conditions (example 1);
- The expected lives of the G2 base and G6 selected layers decreased under the MCL but increased substantially under the MDL;

- The expected life of the in situ subgrade layer decreased under the MCL and increased again under the MDL;
- The traffic demand under the static conditions is for an ES1 traffic class, while under the moving dynamic conditions it moves to an ES3 traffic class.
- The static traffic demand is lower than the static-calculated expected bearing capacity of the pavement, as is the moving dynamic traffic demand and the expected bearing capacity when considering both tyre load population and tyre speed (Section 7.3.6) in the calculation.

In summary, it appears as if the effect of the MCL analysis is to decrease the expected lives of all the layers, while the expected lives of the various layers increase again under the MDL analysis. The decrease under the MCL analysis is to be expected as the tyre load is increased. The increase in expected life under the MDL for the granular layers is mainly because of a reduction in the deviatoric stresses in the layer when the stresses are converted to equivalent dynamic stresses using the equations in Table 6.14. The increase in expected life for the asphalt layer under MDL is due to a decrease in horizontal strain at the bottom of the asphalt layer when the static strain is converted to an equivalent dynamic strain using the equations in Table 6.13.

The increase in expected life for the C3/EG4 subbase layer between MCL and MDL analyses is due to an decrease in the horizontal strains and a decrease in the deviatoric stress (during the granular phase) in this layer.

When the complete pavement is evaluated it appears as if the use of MDL conditions (both tyre load population and equivalent dynamic responses) decreased the expected pavement life by one traffic class (ES10 to ES3) for the conditions under which the analyses were performed. This equates to a decrease of 5,6 million E80s in structural capacity for the specific circumstances. It thus appears from this example as if the effect of moving dynamic loads on the analysis of a pavement structure can be significant. Obviously, the combination of pavement layers and the specific tyre load population will have an effect on the magnitude of the effect.

It is, however, evident from the analyses that the traffic demands are for the first (static) and last (MDL with load population and load speed effects) methods of calculating bearing capacity less than the expected bearing capacity of the pavement structures. It is only when the tyre load population is used in the bearing capacity calculation without the effect of load speed that the traffic demand exceeds the expected bearing capacity for the pavement. These results are unique for the specific conditions used in this example, and cannot be extrapolated to all conditions.

It is recommended that a sensitivity analysis be performed using different road classes and thus tyre load percentiles and pavement response percentiles. Such a sensitivity analysis should indicate the range of expected pavement lives more accurately, as a range of tyre loads and response evaluations would be included. In the example cited in this chapter, the 50th percentile tyre load (for class D roads) is for instance only 22,5 kN. Using this tyre load and the 50th percentile pavement response option in the analysis would lead to an increase in expected pavement life from a class ES3 to a class ES100. It is clear that sound engineering judgement of the specific problem is needed (as for all calculations of expected pavement life) before a final decision on the life of the pavement is made. This is necessary, as the equations are empirical and the transfer functions not originally developed for dynamic load and pavement response.

It is thus recommended that the procedure of evaluating the effect of moving tyre loads and dynamic pavement response be incorporated in a standard pavement analysis to enable the pavement engineer to evaluate the relative effect of vehicle-pavement interaction effects on the specific analysis in question.

7.4 Unresolved issues

7.4.1 Introduction

In order to keep the scope of this thesis manageable, several issues were identified as falling outside the scope of the thesis. These were listed in Chapters 1 and 4 as:

a. Investigate and develop new models and techniques for the vehicle part of the vehicle-pavement interaction system;
b. Generate new data for evaluation with the model;
c. Develop transfer functions for linking the stress and strain output from the model with expected pavement lives and economic issues and,
d. Investigate the surfacing roughness-vehicle interaction.

In the assumptions made regarding data, the following specific assumptions were made:

a. The component characteristics of the population of vehicles can be assumed to be similar to those of a typical vehicle;
b. The characteristics of vehicles do not change with time and use;
c. Vehicles travel in straight lines on level road sections (gradient < 1,5 per cent);
d. The component characteristics of the population of pavements can be assumed to be similar to that of a typical pavement, and
e. The measured and published material parameters used are valid representatives for the typical materials.

In the assumptions made regarding analyses, the following specific assumptions were made:

a. The selected analysis (or simulation) options are representative of typical analysis (or simulation) options;
b. The current SAMDM transfer functions for pavement structures (developed for static loading conditions and response analyses) are valid;
c. The constitutive laws selected for each of the models are valid for the conditions in which they are used;
d. Vehicles travel on the level only, and no significant uphill or downhill travel is part of the analysis;

e. The full effects of pavement roughness can be experienced from a pavement section length of 6 km;
f. All material calculations are done in the total stress mode, and
g. All analysis of material response is performed in the linear elastic mode of response, and no non-linear elastic effects are investigated.

Although these issues fall outside the scope of the current thesis, it does not mean that they are not important. The reasons for making the various assumptions were discussed in Section 4.5. Some of these assumptions (i.e. the material model used) can have a major influence on the pavement response parameters obtained for a specific pavement structure. These specific issues are discussed and suggestions provided for their incorporation into the overall model. An indication of the expected effect of these issues on the outcome of this thesis is also provided. The discussion around their expected effect is not based on further analyses, but rather based on an interpretation of the possible effect using the existing knowledge and understanding of vehicle-pavement interaction of the author. Recommendations are also made for specific further research needed to solve some of these issues.

7.4.2 Vehicle-based assumptions

The characteristics of vehicles do not change with time and use

This assumption influences the simulation of vehicle response to pavement roughness. As vehicle components such as tyres and suspension systems are used they deteriorate and some of their characteristics may change. The net effect of this may be that older suspensions may cause higher dynamic loads than newer suspensions. The effect of tyre deterioration and changes in tyre inflation pressures will also be to change the population of tyre loads applied to the pavement. To combat this phenomenon the vehicle response simulations should ideally be performed using a random combination of suspension and tyre characteristics to generate a population of tyre load populations. These should be combined to form an overall population of tyre loads that incorporate the effects of deteriorating vehicle component characteristics.

The ***effect*** of this assumption is thus that it ignores the changes in tyre loads and contact stresses that may develop due to changes in vehicle characteristics with time. A possible ***solution*** to solve this problem is to use a population of vehicle characteristics (i.e. tyre and suspension condition) from which specific percentiles (depending on the importance of the analysis) are taken for use in the development of a tyre load population.

Vehicles travel in straight lines on level road sections (gradient < 1,5 per cent); Vehicles travel on the level only, and no significant uphill or downhill travel is part of the analysis;

These assumptions cause the tyre loads of vehicles during cornering and / or up or downhill travel to be neglected in the analysis. The effect of this is mainly expected on the surfacing layers of the pavement. When a standard linear elastic multi-layered pavement response analysis is performed (i.e. using ELSYM5M) the effect of this assumption will be negligible as the analysis method does not cater for definition of actual three-dimensional tyre-pavement contact stresses. However, if a finite element analysis is performed where the contact stresses between tyre and pavement can be defined as non-uniform three-dimensional parameters, addition of these parameters will affect the surfacing layer response.

These assumptions also affect the vehicle simulation in terms of the speeds used in the analysis and the contact stresses between the tyre and pavement. Significant uphill and downhill travel will cause the speeds at which vehicles travel to fluctuate. Analysis of the effect of speed on parameters such as the elastic deflection (Section 6.3) has shown that speed affects this parameter directly. Different portions of the pavement will thus react differently to the same nominal tyre load population, due to the load speed. The effect of vehicles moving up- or downhill will also be evident in the tyre-pavement contact stresses.

The ***effect*** of these assumptions is that surfacing deterioration due to non-uniform contact stresses will be ignored in the analysis. Further, the effect of speed on the pavement response on certain sections of the pavement will be ignored. A quick solution to the problem of cornering does not exist. A possible ***solution*** for the assumption regarding speed is to use a conservative speed and empirical equations to establish the equivalent dynamic response of the pavement to the speed at which the load is applied. Fortunately, the standard static analysis provides a conservative estimate of the stresses and strains in the pavement (as shown in Section 7.3.7).

In this thesis it was assumed that all the vehicles had steel suspensions and that the tyre inflation pressures were constant and at the manufacturer's recommended levels at all times. However, some operators do use air suspension (and other systems) and often operators use their tyres with tyre inflation pressures outside the manufacturer's recommended levels.

The ***effect*** of using air suspension on the pavement is generally to lower the dynamic loads on the pavement – if the suspension is well maintained (or to lower the Coefficient of Variation of the tyre load population). A ***solution*** to this problem in vehicle-pavement interaction analyses is to use a lower CoV when developing the tyre load population. Preferably, simulations should be performed to establish the level to which the CoV may be lowered.

The ***effect*** of using different tyre inflation pressures is to either increase (higher tyre inflation pressures) or decrease (lower tyre inflation pressures) the Coefficient of Variation of the tyre load population. Higher tyre inflation pressures will effectively increase the stiffness of the suspension, thereby causing less damping of the pavement roughness. Lower tyre inflation pressures will effectively decrease the stiffness of the suspension thereby absorbing more of the pavement roughness effects through the tyres. A possible ***solution*** to this problem is again to use a conservative tyre inflation pressure (thus a higher value) in the development of a tyre load population.

7.4.3 Pavement-based assumptions

Development of new transfer functions for linking the stress and strain output from the model with expected pavement lives and economic issues falls outside the scope of this thesis. The current SAMDM transfer functions for pavement structures (developed for static loading conditions and response analyses) are valid

The ***effect*** of these two assumptions is that transfer functions developed based on static analysis of slow-moving tyre loads are used to calculate the effect of moving dynamic loads on a pavement structure. The specific effects will differ depending on the material type present in the pavement structure. Frequency-dependent materials such as asphalt are obviously influenced by this assumption more critically than non-frequency-dependent materials such as granular materials.

A possible **solution** for this problem is to develop empirical equations to convert static response parameters to equivalent dynamic response parameters (Section 6.5). It is important to realise that such equations are empirical equations that are strictly only valid for the conditions (layers, depth, thickness and combination of layers) for which they were developed. It is recommended that further research in this regard be performed to obtain more mechanistic models to assists with this transition.

All analysis of material response is performed in the linear elastic mode of response, and no non-linear elastic effects are investigated.
The ***effect*** of this assumption is that non-linear response due to the movement of the tyre load and the varying nature of the tyre load are not accounted for in the analysis. This will especially be a problem when the dynamic response of frequency dependent materials is calculated. Ignoring the non-linear material response will lead to the permanent deformation behaviour of the pavement structure to be ignored in the analysis.

A possible **solution** may be to develop empirical transfer functions for converting between linear elastic and non-linear response types.

The issues of risk and reliability in pavement design have not been addressed in this thesis. It is, however, important to have an understanding of the effect of reliability of input data such as pavement layer thicknesses, pavement roughness and vehicle component characteristics on the output of the pavement design process. It is therefore recommended that when vehicle-pavement interaction is incorporated in the pavement design process, the effect of some variation in the input data on the calculated pavement lives and structures be determined. The risk associated with use of an erroneous input value should also be determined.

It was stated in Section 6.3 that attempts were made to perform a 3-dimensional finite element analysis of the vehicle-pavement interaction problem of a vehicle running on a pavement applying a Moving Dynamic Load (MDL) to the pavement, and the pavement's response to this load. However, this analysis proved technically complicated due to the memory and analytical requirements for doing such an analysis. Although the analysis is possible to perform, the computing power and software available to the author did not allow such an analysis to be performed cost- and time-effectively.

In addressing the possible effect of such an analysis on the problem of vehicle-pavement interaction, the additional parameters and interaction effects to be accounted for in such an analysis, and the expected outcome of the analysis are important.

The additional parameters to be accounted for in this analysis (as opposed to the Moving Constant Load (MCL) axi-symmetric finite element analysis performed in Section 6.3) are mainly the varying nature of the tyre load and the time-varying pavement response due to the varying tyre load. This also forms the main additional interaction effect introduced in this analysis. The typical load frequencies for tyre loads are in the ranges of 1 to 4 Hz (body bounce) and 10 to 18 Hz (axle hop) (Section 2.3.2). This is the rate at which the load magnitude changes with time. These tyre loads are applied to the pavement at speeds that typically ranges between 5 km/h (creep speed) and 100 km/h. If a tyre contact patch length of 300 mm is assumed (as in Chapter 5) it translates to speed frequencies of between 4,6 Hz (5 km/h) and 92,6 Hz (100 km/h).

Two sets of frequencies thus exist. These are the frequency at which the load magnitude changes and the frequency at which the load position changes. It is the hypothesis (that will not be evaluated in this thesis) of the author that if the load position frequency is higher than the load magnitude frequency, (thus the position changes quicker than the magnitude) the problem can be reduced to a Moving Constant Load (MCL) problem. This would be the case for all speeds higher than approximately 21 km/h (20 Hz). For normal road speeds the assumption will thus be correct.

The above discussion would be true as the load at any one discrete tyre print location (300 mm long in this discussion) can be assumed not to change during its application. The load history can thus be broken into discrete constant loads that are applied to the pavement at specific intervals. The problem can then be simplified by using the more critical load magnitudes in a MCL analysis. This approach will simplify the analysis technique as only MCL inputs will have to be incorporated.

Another interaction effect is the response of the pavement to tyre loads applied in quick succession (as for a number of axles that move over a specific position at speed). Other researchers (i.e. De Beer, 1991) have shown the effect of loads in short succession to increase the maximum load response magnitude in a pavement. In the case of a MDL the applied loads at successive positions will vary, causing the cumulative pavement response to depend on the varying value of the load magnitude. This effect should, however, be conservatively estimated by performing a MCL analysis using a higher percentile load magnitude.

It thus appears as if a 3-dimensional vehicle-pavement interaction analysis using finite elements can be simplified by using a 3-dimensional MCL analysis. This MCL analysis should provide a conservative estimate of the pavement response. It is recommended that a more complete investigation of a 3-dimensional vehicle-pavement interaction simulation and analysis be performed to evaluate the results of such an analysis and to also verify the possibilities of using the simplifications discussed.

In this thesis the emphasis was on vehicle-pavement interaction analysis using both vehicle and pavement structure simulations. This was done mainly due to a lack of funding to perform complicated measurements of real tyre loads and pavement response parameters in the field. Although the tools used in this thesis are seen to be validated for the conditions under which it was used, it is also recommended that further work be performed to physically measure and validate the major findings of this thesis.

7.5 Observations

The following observation is made based on the information in this chapter:

- Vehicle-pavement interaction is a complex process where the properties of both the vehicle and the pavement play important roles that ultimately cause the deterioration of the pavement structure.

7.6 Conclusions

The following conclusions are made based on the information in this chapter:

- The use of percentile values of the dynamic tyre load population rather than an equivalent static 80 kN axle load in pavement response analyses causes significantly different pavement responses;
- The use of moving dynamic loads and equivalent dynamic pavement response parameters in pavement analyses is possible and provides good estimates of the expected pavement life;
- The use of a range of percentile values and input data values can assist in determining a population of pavement response values from which a better understanding of the vehicle-pavement interaction under all conditions can be extended, and
- Moving constant and moving dynamic loads can affect pavement response analyses significantly and should be applied with good engineering judgment.

7.7 Recommendations

The following studies are recommended based on the information in this chapter:

- A study to determine the mechanistic relationship between vehicle characteristics and pavement roughness to develop mechanistic equations for predicting the tyre load populations of vehicles;
- A study to develop a 3-dimensional transient vehicle-pavement interaction model that can be used to model the moving dynamic load transient response of a pavement structure;
- A study to develop mechanistic relationships between static and dynamic response parameters for typical pavement materials;
- A study on the effect of different input parameters on the reliability of the output from a typical vehicle-pavement interaction analysis, and
- A study to validate the important findings of this thesis (i.e. pavement deterioration) with actual tyre loads and in situ measurements (field observations) of pavement response.

7.8 References

DE BEER, M. 1991. **Pavement response measuring system.** Paper presented at the 2nd International Symposium on Pavement Response Monitoring Systems for Roads and Airfields, September 6-9, Hanover, New Hampshire, USA.

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).

GILLESPIE, T.D. 1992. **Fundamentals of vehicle dynamics.** Warrendale, PA: Society for Automotive Engineers.

SAYERS, M.W., GILLESPIE, T.D. and QUEIROZ, C.A.V. 1986. **The international road roughness experiment. Establishing correlation and a calibration standard for measurements.** Washington, D.C., USA: World Bank. (World Bank Technical Paper Number 45).

THEYSE, H.L, DE BEER, M. and RUST, F.C. 1996. **Overview of the South African Mechanistic Design Method.** In: Pavement design, management and performance. Washington, DC: Transportation Research Board, National Research Council (Transportation Research Record; 1539) pp 6-17.

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.

8. OBSERVATIONS, CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

In this chapter an indication of the contribution of the thesis to the state of knowledge is first provided. This is followed by the main observations, conclusions and recommendations from this thesis.

The thesis focuses on providing practical guidelines to characterising vehicle-pavement interaction from a pavement design viewpoint. The objectives of this study focus on a practical systems framework populated with various models and data sets for the analysis of the transient response of pavement structures to dynamic tyre loads. The stated objectives of this study were met by developing such a framework and a practical approach for analysis of vehicle-pavement interaction, and by verifying this approach using existing analysis techniques. The overall scope of this thesis was the field of vehicle-pavement interaction, focussing on the effect of vehicle-pavement interaction specifically on pavement design.

8.2 Contribution to the State of Knowledge

The aim of this thesis is to contribute to the state of knowledge in the general field of vehicle-pavement interaction, with a focus on the effects on pavement design. The main areas where this thesis contributes to the state of knowledge are:

a. Development of a method for predicting the moving dynamic tyre load on a pavement based on relevant vehicle and pavement parameters;
b. Development of a method for estimating the dynamic pavement response parameters based on the static pavement response parameters for certain pavement structures;
c. Definitions for the type of loads on pavements and the technological analysis types available for vehicle-pavement interaction studies, and
d. A better understanding of the issues relevant to vehicle-pavement interaction from a pavement design viewpoint in South Africa.

The *method for prediction of the moving dynamic tyre loads on pavements* is based on the knowledge that tyre load populations form a normal distribution, and that the average and Coefficient of Variation of this normal distribution can be predicted based on certain vehicle and pavement properties (Equations 5-1 and 5-2).

These equations contribute to the practice of pavement engineering in South Africa in that it can be used to develop moving dynamic tyre load populations for existing pavements in South Africa to aid the process of pavement management and rehabilitation. Individual tyre load populations can be developed for each section of pavement, ensuring optimum managerial decisions on maintenance and rehabilitation options and strategies.

The *method for estimating the dynamic pavement response parameters based on static pavement response parameters* is based on empirical relationships between the static and dynamic pavement response parameters calculated using an axi-symmetric finite element analysis method (Tables 6.13 and 6.14). It can be used to obtain indications of the effect of speed on pavement response for certain pavement types.

These equations contribute to pavement design in providing a tool to the general pavement engineer to evaluate the possible effects of load speed on the population of possible pavement bearing capacities for a specific structure. Although these equations are empirically derived (and therefore unique for the conditions for which they were derived) it forms the beginning of a better understanding of the issue of load speed in pavement design.

The *definitions for load types and technological analysis for vehicle-pavement interaction studies* assist in the understanding of the primary issues concerning vehicle-pavement interaction issues. It can be used to base further investigations into detailed aspects of vehicle-pavement interaction on. It also assists in focussing the pavement engineer on the relevant issues in vehicle-pavement interaction.

The analyses and discussions contained in this thesis add to the current knowledge of vehicle-pavement interaction from a pavement design viewpoint in South Africa, by highlighting dominant and important issues in such analyses. The examples in Section 7.3 form the basis of indicating the need for incorporating vehicle-pavement interaction issues into normal pavement design and analysis. The effect of inadequate pavement maintenance and the resultant effect of inadequate pavement roughness on moving dynamic tyre loads necessitate a new appreciation of issues such as quality control and pavement management to ensure prime pavement quality for the life of the pavement.

It was stated in Chapter 1 of this thesis that it is the purpose of this study to contribute to the state of knowledge in terms of:

a. Establishment of a holistic system approach to vehicle-pavement interaction in which the connections between the various components are defined;
b. Provision of a simplified method for estimating the moving dynamic tyre load on a pavement, and
c. Provision of a practical approach to transient pavement-structure response analyses for evaluating specifically South African pavement structures.

It is the author's view that these objectives have been met and that an improved understanding of vehicle-pavement interaction for pavement design exists due to the contribution of this study. However, much still needs to be done to improve this understanding and it is also the plea of the author that the recommendations in this thesis be taken further to ultimately aid in the economic development of South Africa by ensuring a high-quality pavement network.

8.3 Observations

The following primary observations are made based on the information in this thesis. These observations may in some cases confirm existing knowledge, but are highlighted as they are seen to be vital for a clear understanding of the effects of vehicle-pavement interaction in pavement design. The chapter on which the specific observation is based is shown in brackets:

a. Difficulties were experienced in obtaining valid information on both vehicle and pavement components (Chapter 2);
b. The vehicle-pavement interaction process can be classified into various components that interact with each other in specific manners (Chapter 4);
c. Load magnitude shows good relationships with the stresses in the upper part of the pavement structure, while load speed shows good relationships with the strains in the pavement structure (Chapter 6);
d. Higher load frequencies affect calculated stresses in the pavement less than calculated strains. Higher load frequencies affect calculated strains in the deeper parts of the pavement less than lower load frequencies (Chapter 6);
e. Analysis of response parameters indicated that the deeper parts of the pavement are less affected under moving constant loads (MCL) than under static loads (Chapter 6);
f. A distance lag exists with speed between the position of maximum load application and the positions of maximum response at the surface and lower down in the pavement (Chapter 6);
g. Running finite element analyses is a time-consuming process that requires detailed input data and data reduction techniques not normally required for static response analyses. More complicated material models affect the time required for an analysis (Chapter 6);
h. Similar trends were observed in both the static pavement response and transient pavement response analyses for all parameters at the different load levels (Chapter 6), and
i. The equations for converting static response parameters to equivalent dynamic response parameters appear to provide good relationships (Chapter 7).

8.4 Conclusions

The following primary conclusions are drawn based on the information in this thesis. More conclusions of a general nature can be found at the end of each chapter. Some of the conclusions may confirm existing knowledge, but are highlighted as they are seen to be vital for a clear understanding of the effects of vehicle-pavement interaction in pavement design. The chapter on which the specific conclusion is based is shown in brackets:

a. Pavement roughness is the main cause for dynamic tyre loads (Chapter 2);
b. The main vehicle components identified as important in vehicle-pavement interaction are the tyres, suspension, vehicle dimensions, configuration and load (Chapter 2);
c. A thorough fingerprinting of the important pavement and vehicle issues should be performed on a regular basis to ensure availability of valid data to industry (Chapter 2);

d. Vehicle speed, stress level and environmental conditions were identified as the major factors in influencing transient pavement response (Chapters 2, 5 and 6);

e. A good understanding of material properties is needed if a transient pavement response analysis is attempted (Chapter 6);

f. All tyre loads can be classified as Static, Moving Constant, Dynamic or Moving Dynamic Loading (Chapter 4);

g. All pavement responses to tyre loading can be classified as either Static or Transient Response (Chapter 4);

h. The static tyre load component is directly related to the Gross Vehicle Mass (GVM) of the vehicles that use the pavement, while the dynamic load component is directly related to and dependent on the vehicle speed, vehicle type, GVM, load and pavement roughness (Chapter 5);

i. 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) (Chapter 5);

j. Load magnitude has a dominant effect on the calculated stresses using moving constant load analyses, especially in the surfacing and base layers of the pavement, while load speed has a dominant effect on the calculated strains and deflections in the pavement (Chapter 6);

k. The positions of maximum load application and maximum stress response at the different depths in the pavement are not similar when the load is moving, and it increases with increased load application speeds (Chapter 6);

l. This distance lag indicates that a relative principal axis rotation occurs between the upper and the lower parts of the pavement when a load is moved over a pavement (Chapter 6);

m. Use of the transfer functions developed for static conditions together with data from a moving constant load analysis do not provide the same estimates of pavement life than when static load analysis are used exclusively (Chapter 7);

n. The use of percentile values of the dynamic tyre load population, rather than an equivalent static 80 kN axle load in pavement response analyses cause significantly different pavement responses which ultimately can be used to develop a population of possible pavement responses (Chapter 7);

o. The use of moving dynamic loads and equivalent dynamic pavement response parameters in pavement analyses is possible and can provide adequate estimates of the expected pavement life (Chapter 7), and

p. Moving constant and moving dynamic loads can affect pavement response analyses significantly and should be applied with good engineering judgment (Chapters 6 and 7).

8.5 Recommendations

The following primary recommendations are made based on the information in this thesis. The chapter on which the specific conclusion is based is shown in brackets:

a. A sensitivity analysis of the effect of variations in vehicle and pavement component characteristics on pavement response analysis should be performed (Chapters 2, 5 and 6);

b. A study should be performed to determine the mechanistic relationship between vehicle characteristics (i.e. combination, and component types) and pavement roughness to develop mechanistic equations for predicting the tyre load populations of vehicles (Chapter 5);

c. The effect of accelerating, decelerating and cornering on dynamic tyre loads should be investigated (Chapter 5);

d. The effect of different suspension systems on dynamic tyre loads should be investigated (Chapter 5);

e. The effect of actual (non-uniform) contact stresses between tyres and the pavement during dynamic tyre loading should be investigated (Chapter 5);

f. An investigation regarding improvement of current transfer functions to incorporate moving dynamic loads and non-linear elastic material models on South African pavements should be performed (Chapter 6);

g. The effects of non-linear (and other) material models on vehicle-pavement interaction should be investigated (Chapter 6);

h. A study should be performed to develop a simple 3-dimensional transient vehicle-pavement interaction model that can be used to model the moving dynamic load transient response of a pavement structure (Chapters 6 and 7), and

i. A mechanistic relationship should be developed between the static and dynamic response parameters of various pavement materials to enable a mechanistic (and not empirical as in this thesis) conversion between static and dynamic response parameters (Chapters 6 and 7).

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).

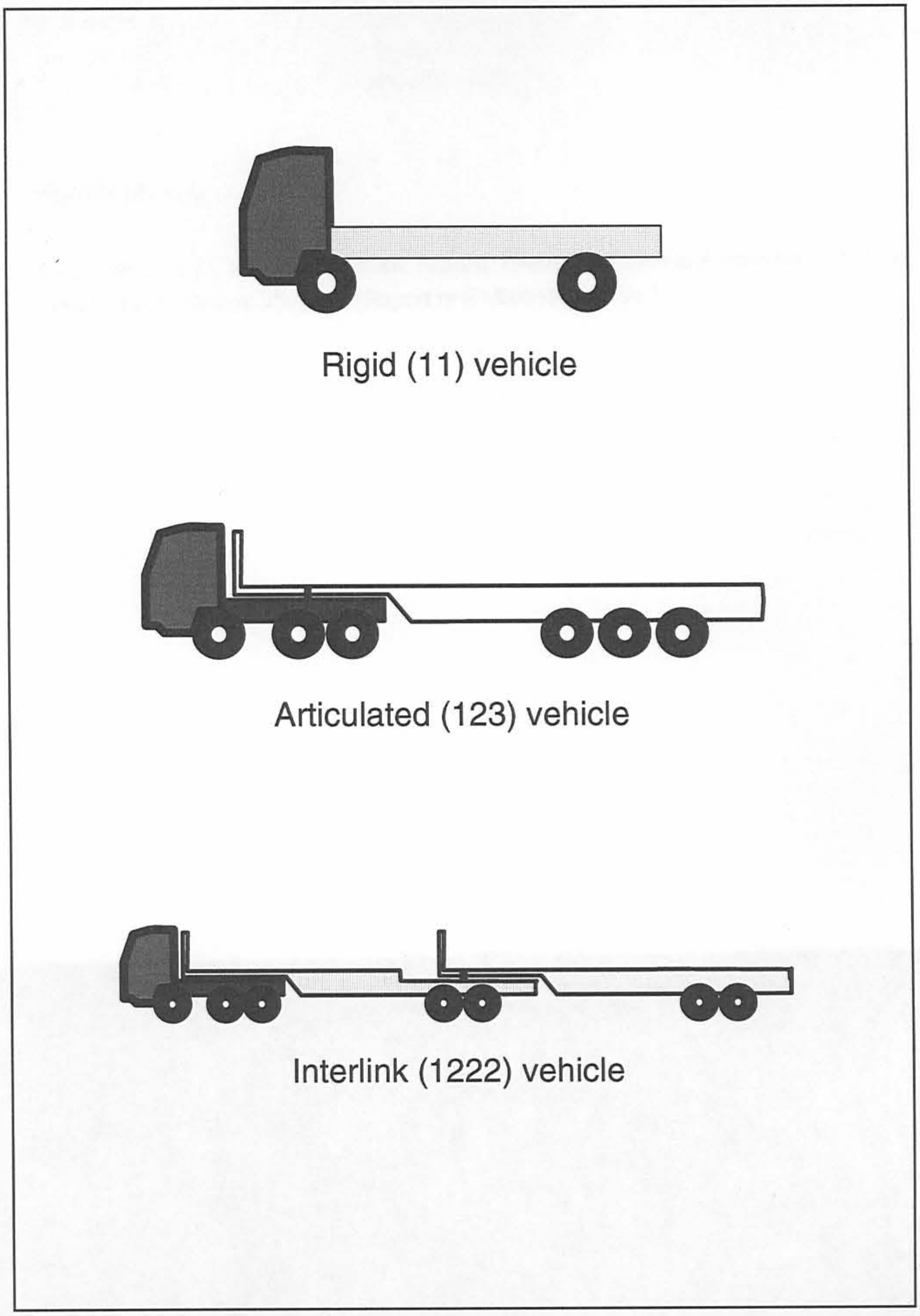
The data shown in this appendix are referred to in Chapters 2.3.2 and 4.6.1 and used for the vehicle simulations described in Chapter 5.

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



Rigid (11) vehicle

Articulated (123) vehicle

Interlink (1222) vehicle

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.

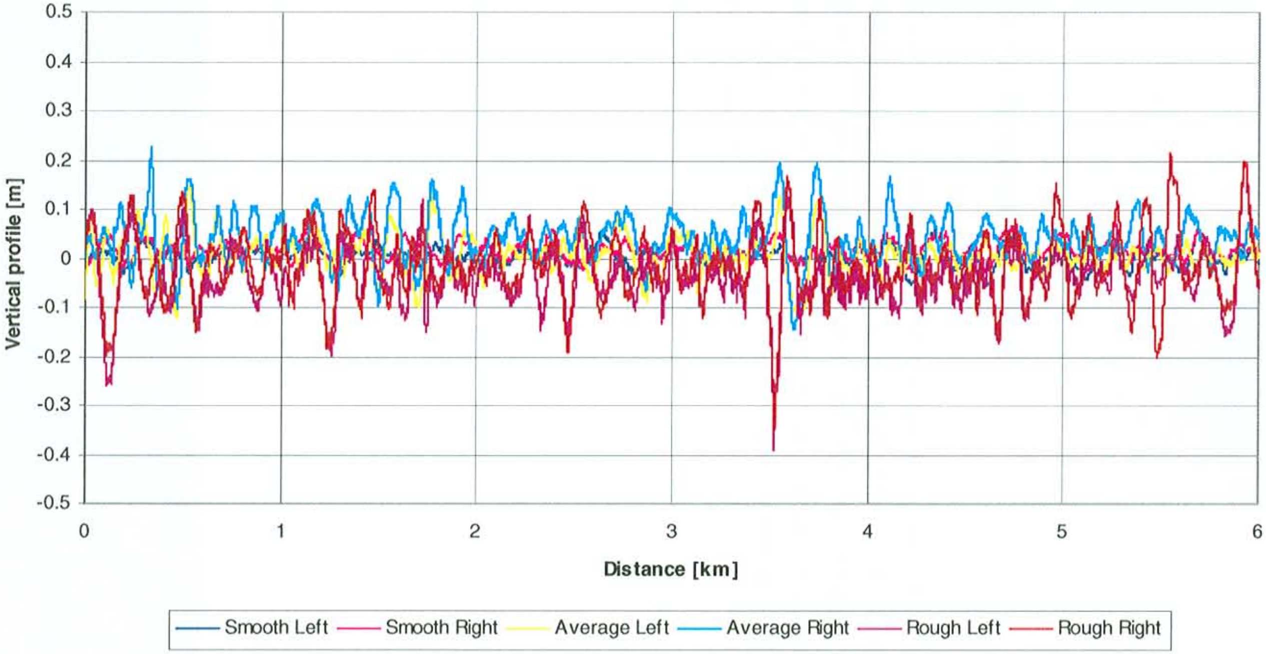


Figure B.1: Pavement profiles of three selected pavement sections (left and right wheeltracks)

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.

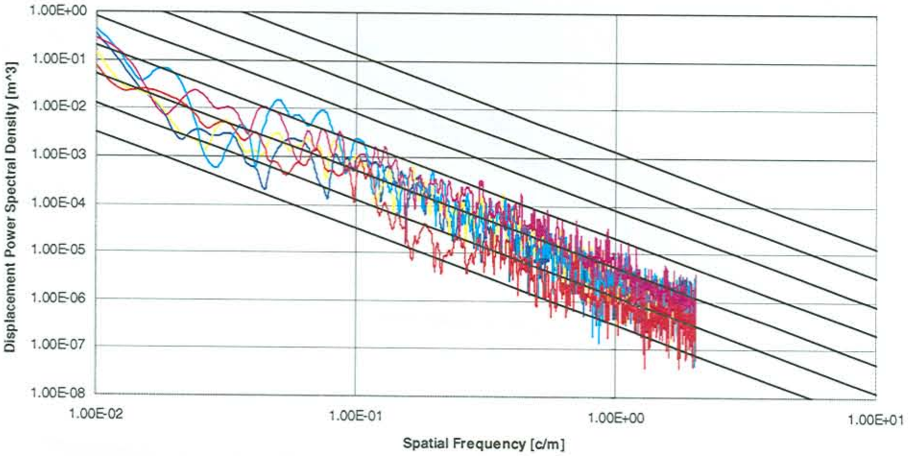


Figure B.2: Displacement Power Spectral Density (PSD)-based ISO classification of Smooth pavement test section for left wheeltrack in 1,0 km sections.

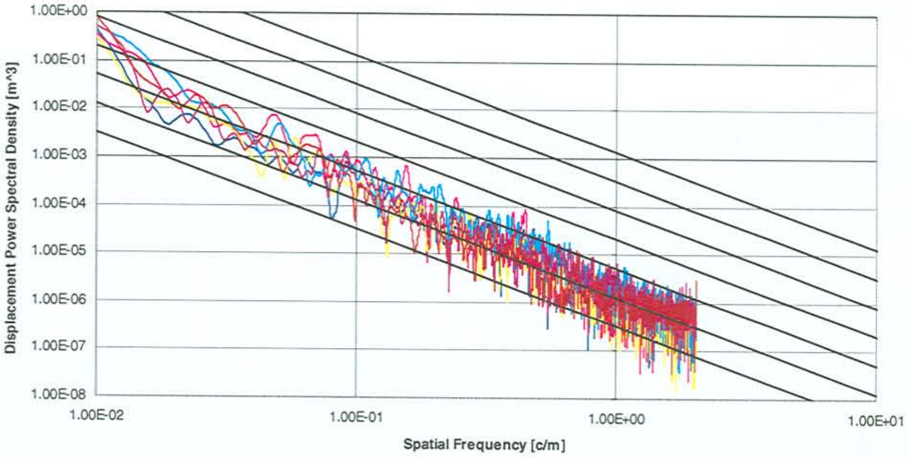


Figure B.3: Displacement Power Spectral Density (PSD)-based ISO classification of Smooth pavement test section for right wheeltrack in 1,0 km sections.

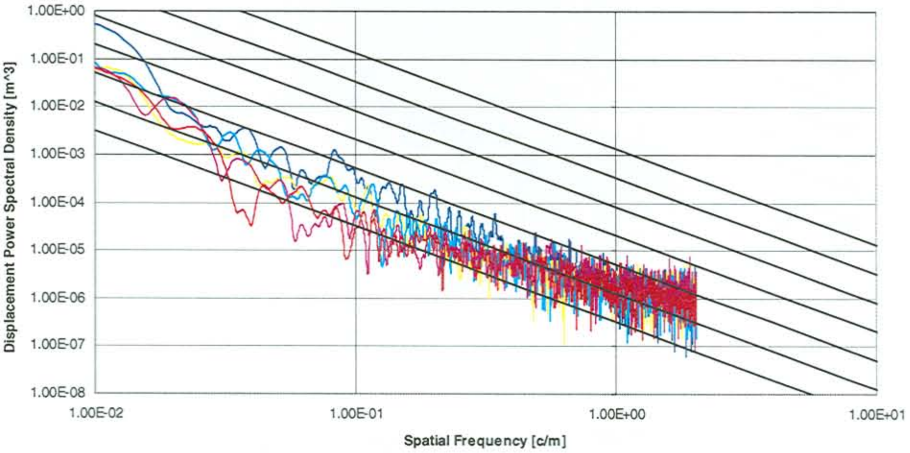


Figure B.4: Displacement Power Spectral Density (PSD)-based ISO classification of Average pavement test section for left wheeltrack in 1,0 km sections.

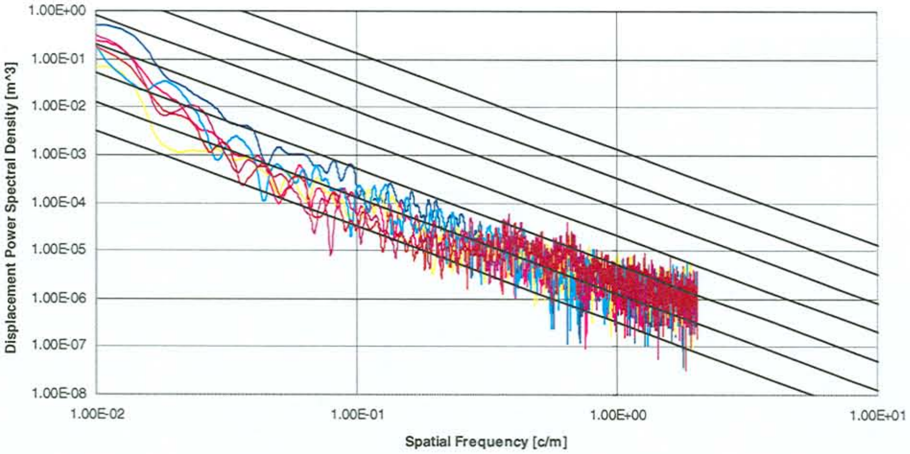


Figure B.5: Displacement Power Spectral Density (PSD)-based ISO classification of Average pavement test section for right wheeltrack in 1,0 km sections.

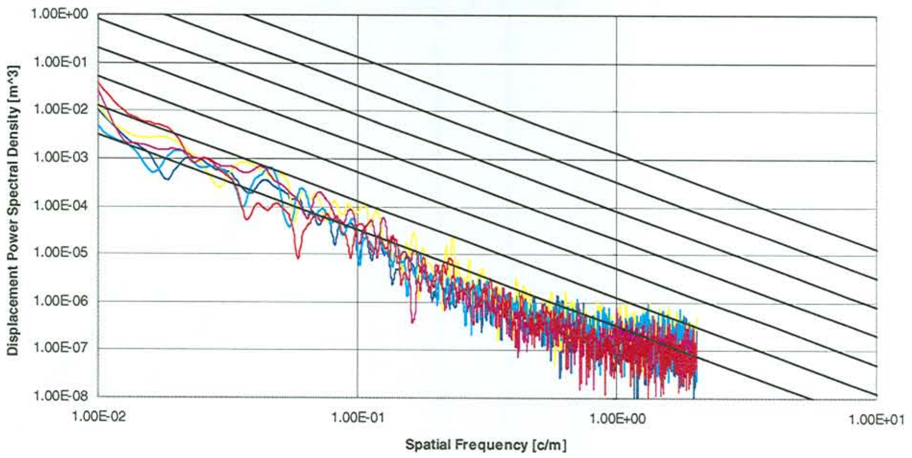


Figure B.6: **Displacement Power Spectral Density (PSD)-based ISO classification of Rough pavement test section for left wheeltrack in 1,0 km sections.**

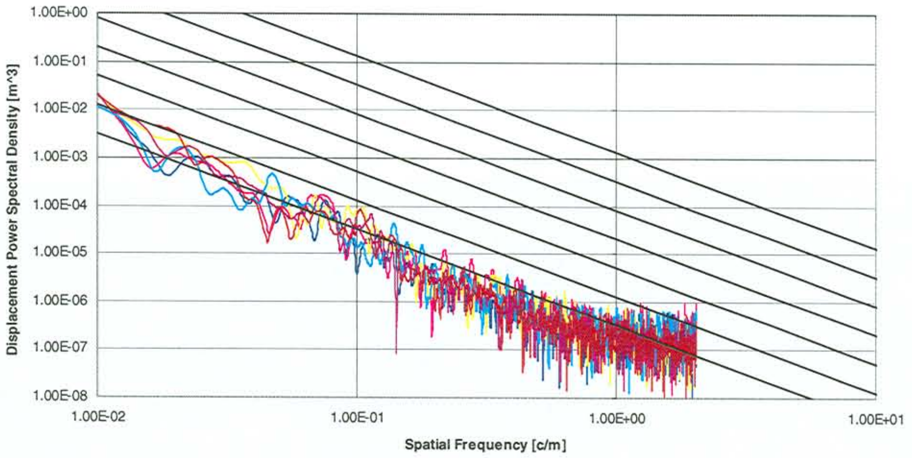


Figure B.7: Displacement Power Spectral Density (PSD)-based ISO classification of Rough pavement test section for right wheeltrack in 1,0 km sections.

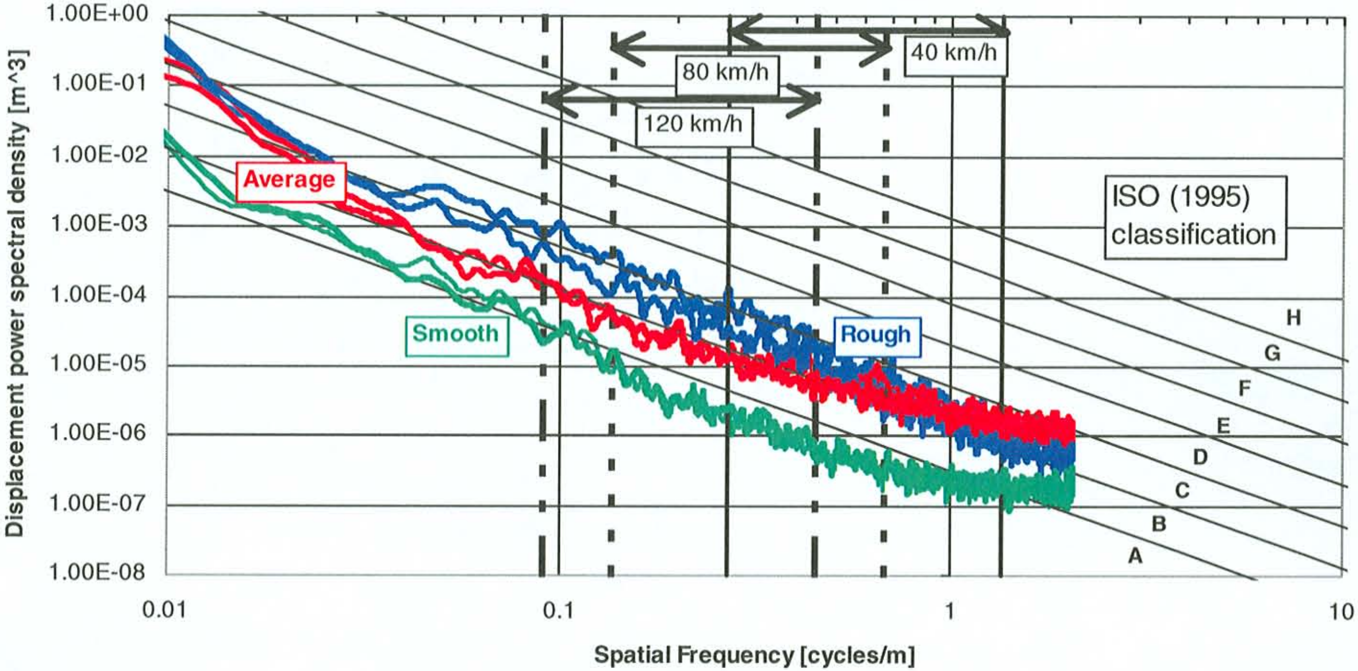


Figure B.8: Displacement Power Spectral Density (PSD)-based ISO classification of all three pavements.

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 mil[1]	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

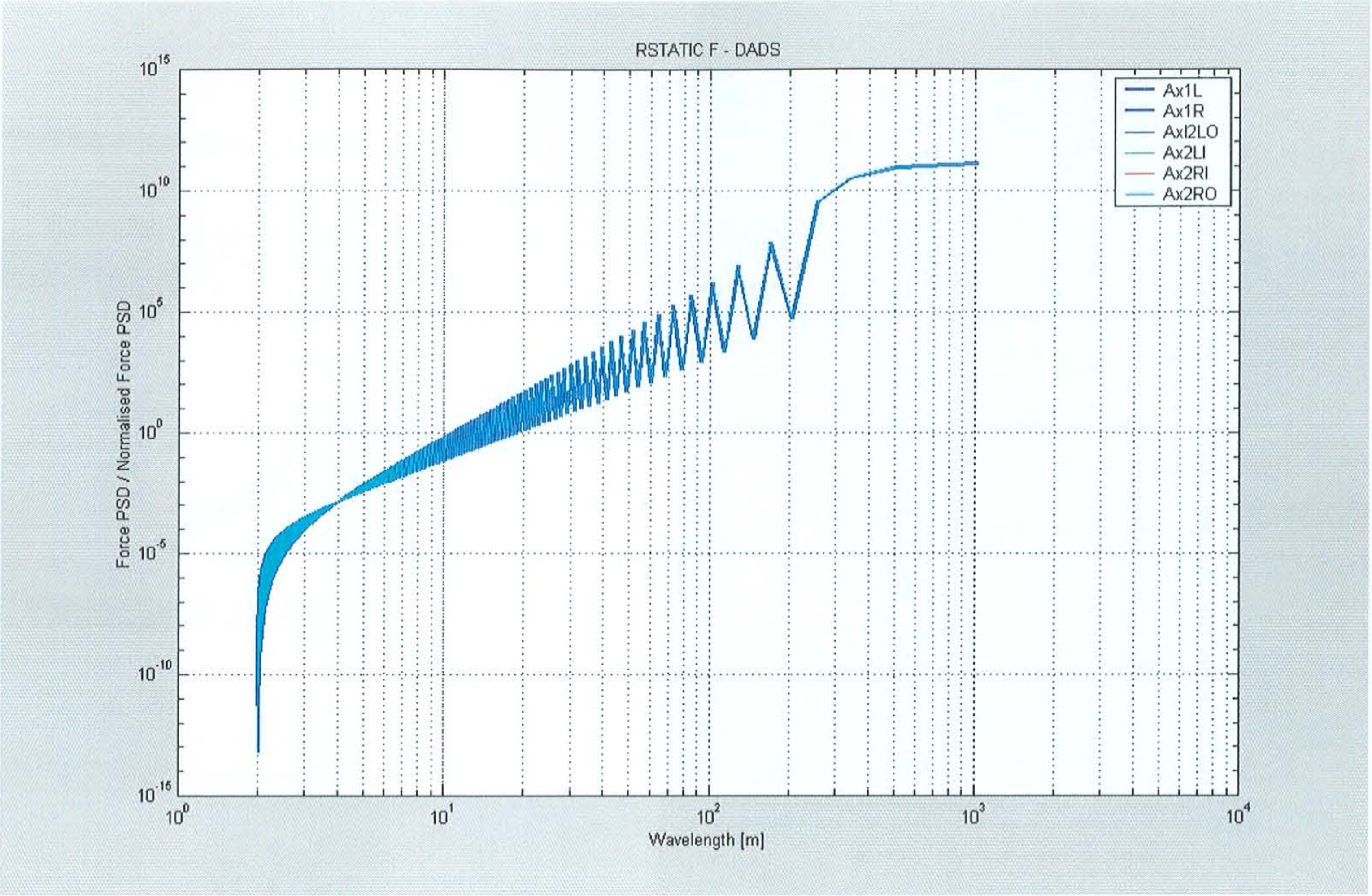


Figure C.1: **PSD of static tyre load indicating frequency band at ultra low (> 100 m) wavelengths.**

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.