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 <u>underlined</u> 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).

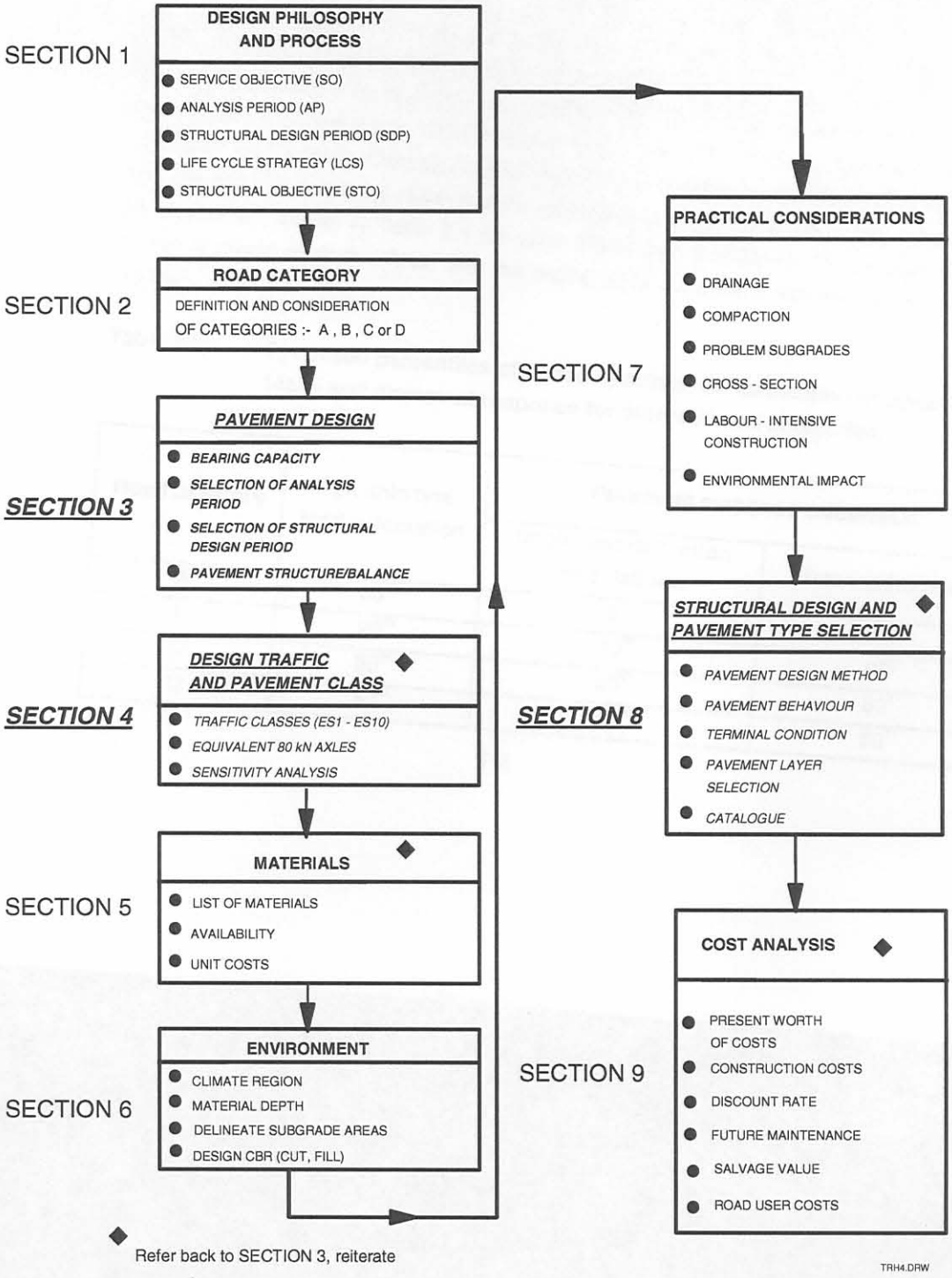

Figure 7.1: Detailed road pavement design process (TRH4, 1996).

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

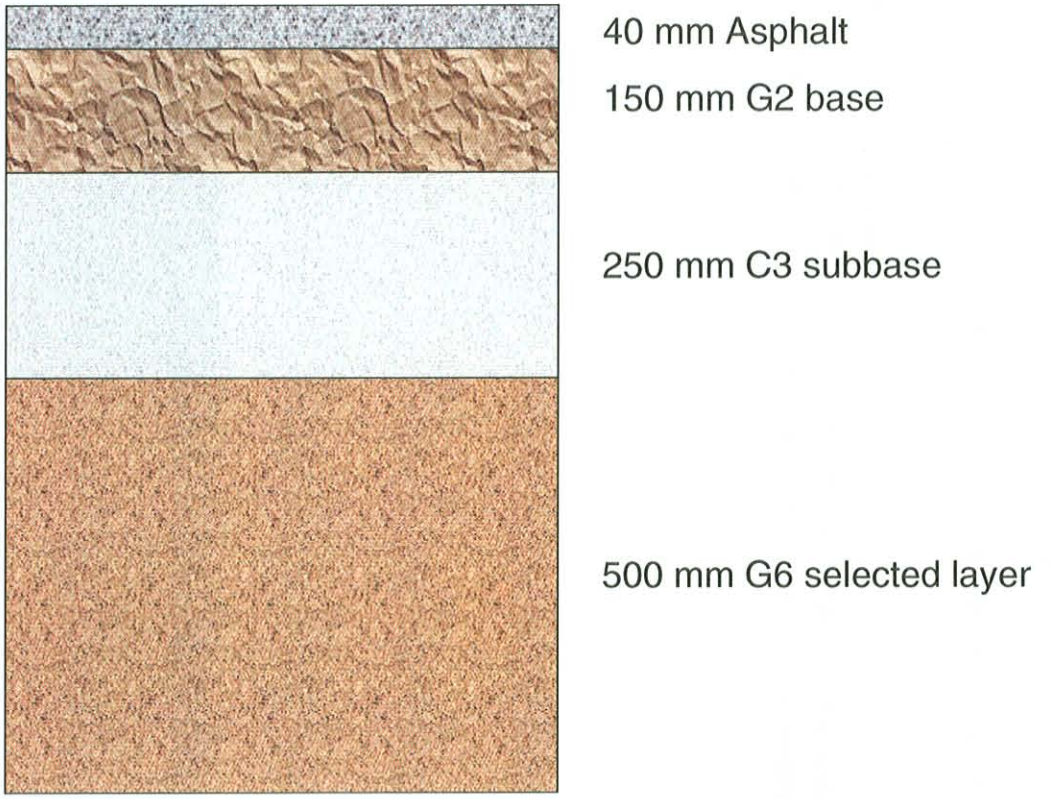

Figure 7.2: Nominal pavement structure used for examples of vehicle-pavement analysis.

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.
$AADE_{initial}$ = AADE = 86,6.
Cumulative factor = 11 303.
E80 total = $AADE_{initial}$ 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.

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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.

$AADE_{initial}$ = AADE = 164,2 (new pavement); 170,9 (terminal condition).

Cumulative factor = 11 303.

E80 total = $AADE_{initial}$ 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.

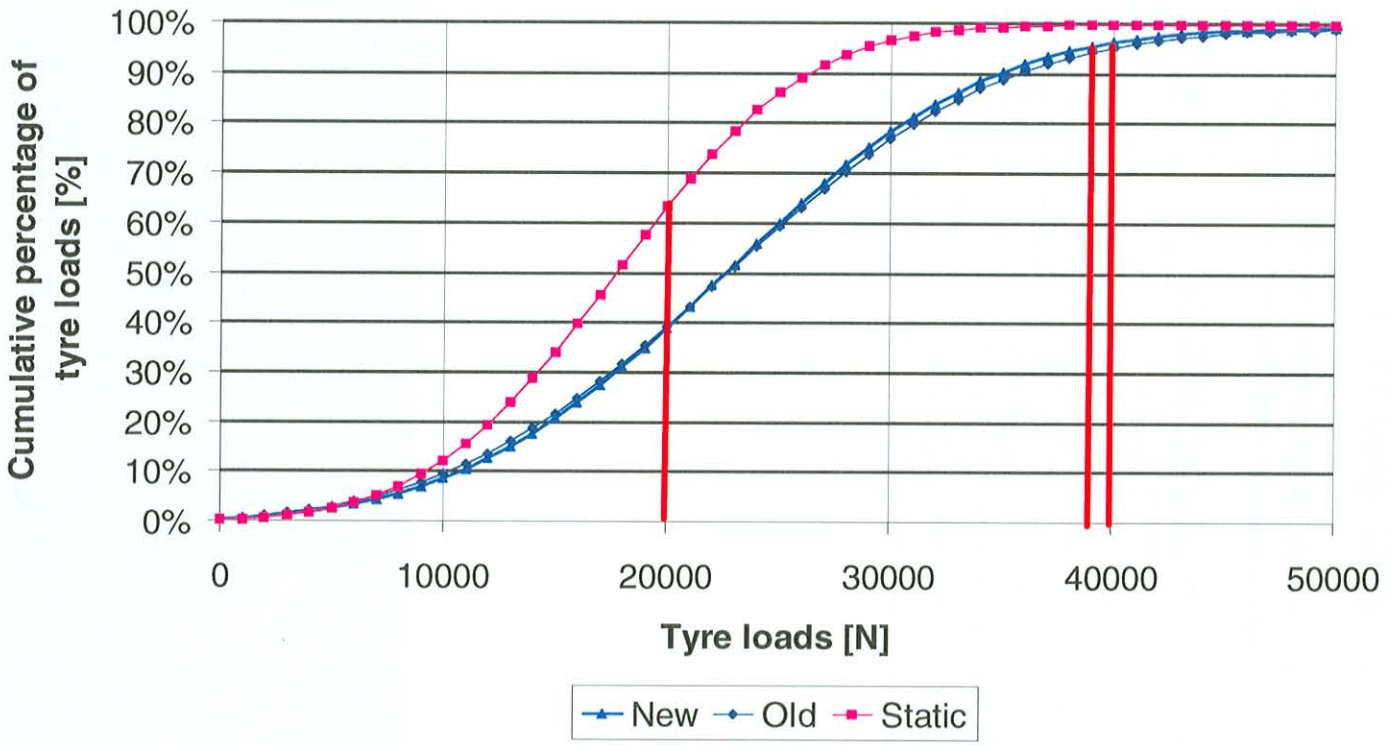

Figure 7.3: **Cumulative tyre load distributions used for examples of vehicle-pavement response analysis.**

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

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