

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).

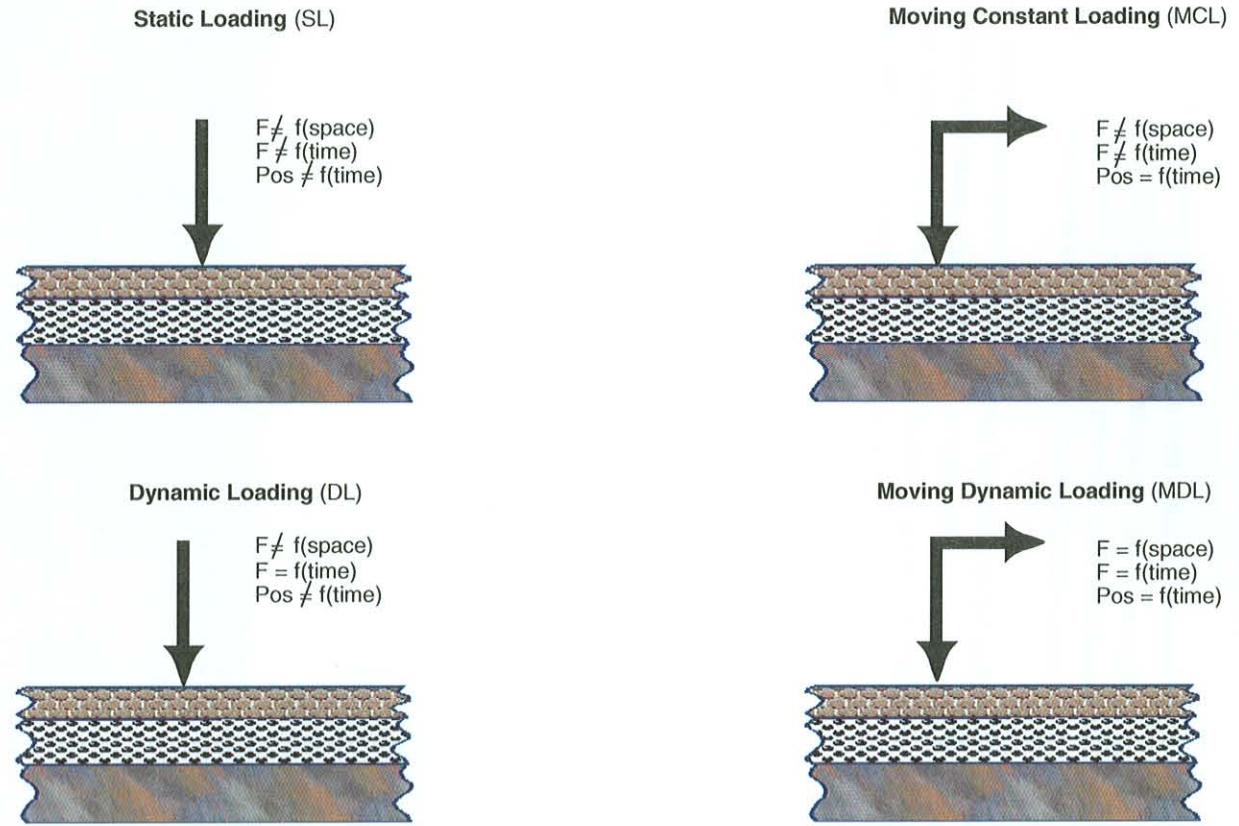


Figure 4.1: Four types of loading modes.

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.

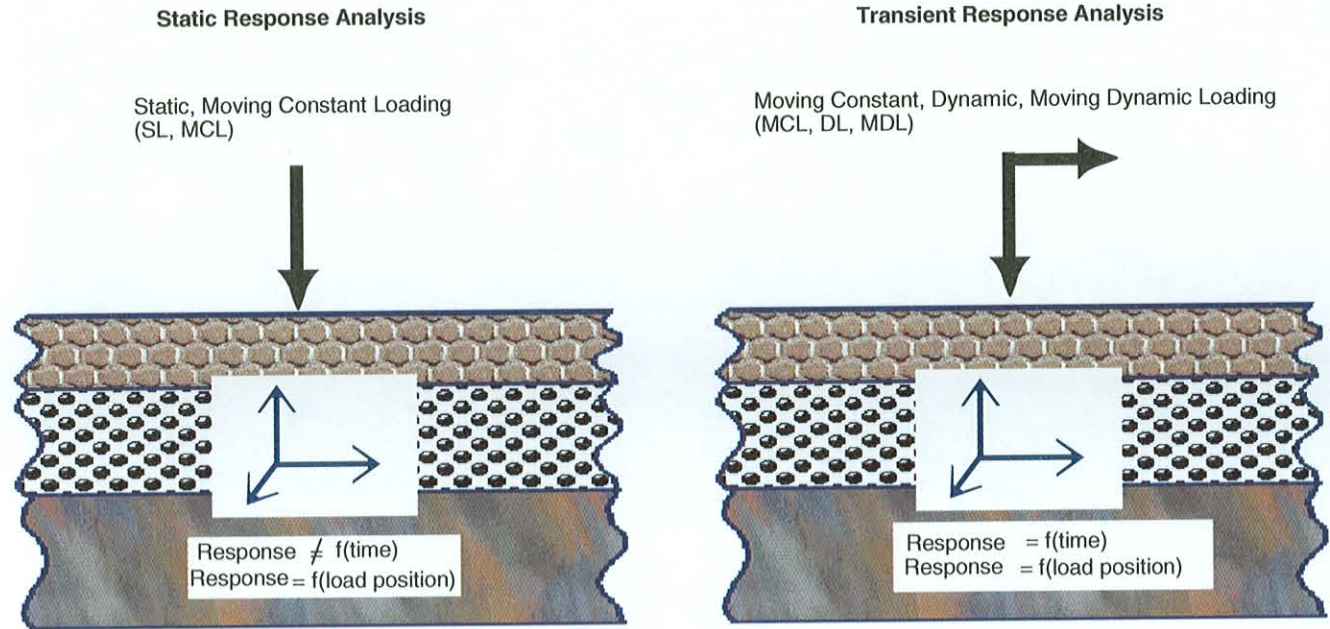


Figure 4.2: Two types of response modes.

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 configuration, dimensions	3-dimensional movement in vehicle structure
	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 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.

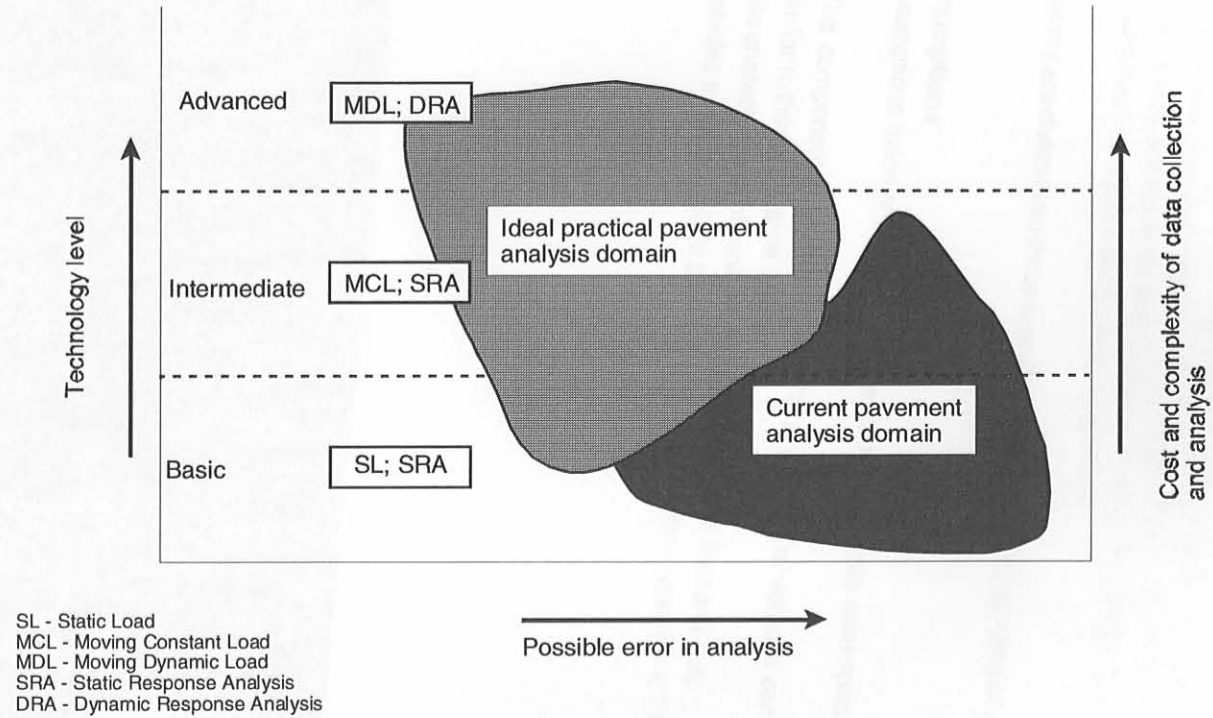


Figure 4.3: Schematic indication of the possible relationship between the possible error, costs and efforts needed in performing an analysis for various technology levels defined in this thesis.

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 (Gilliomme, 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 (Gilliomme, 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.

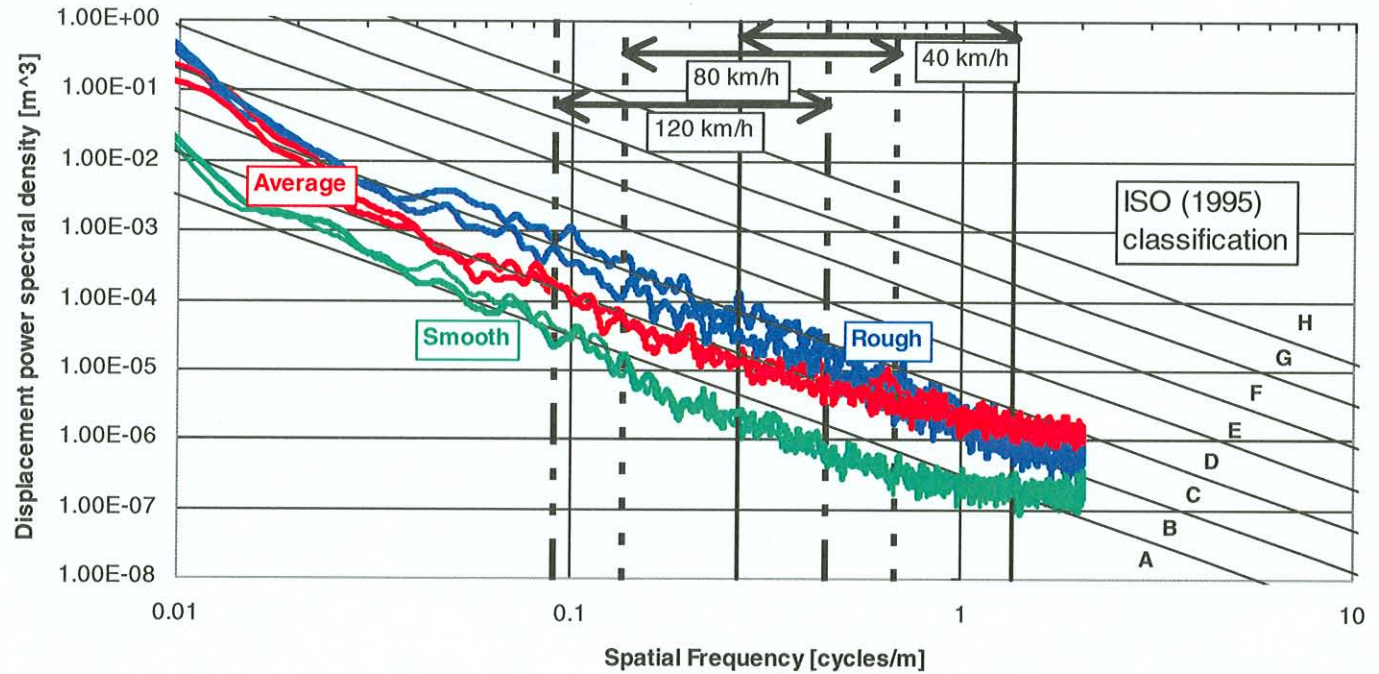


Figure 4.4: Displacement Power Spectral Densities (DPSDs) on ISO classification for all three pavements.

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	ν	0,12
Damping coefficient	d	0,22
Mass density [kg/m ³]	ρ	2 300
Double seal		
The double seal does not possess 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	ν	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	ν	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	ν	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	ν	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	ν	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	ν	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.

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