CHAPTER 1

INTRODUCTION AND PROJECT DEVELOPMENT

1.1 Introduction

The expansion of surface mining in South Africa and in particular coal strip mining, has led to the development of very large off-highway trucks currently capable of hauling payloads in excess of 160t. Typical axle loads ranging from 110t to 170t are applied to haul roads that have been, at best, empirically designed on the premise of "satisfactory" or "failed". This design method served its purpose in an era when off-highway trucks were lighter and less financial outlay was required, both in terms of initial pavement construction costs, ongoing maintenance costs and vehicle maintenance costs. Currently, truck haulage costs can account for between 10%-20% of the total costs incurred by a strip mine and as the trend in increasing truck size continues, the current pavement systems have proved inadequate. Not only would the maintenance costs of existing roads of inadequate thickness increase, vehicle operating and maintenance costs would also increase prohibitively.

Equally important as the structural strength of the design, is the functional trafficability of the pavement. This is dictated to a large degree through the choice, application and maintenance of wearing course materials. The current functional performance analysis methods are subjective and localised in nature and any deterioration in pavement condition consequently hard to assess. Poor functional performance is manifest as poor ride quality, excessive dust, increased tyre wear and damage and an accompanying loss of productivity. The corollary of these effects is seen as an increase in overall vehicle operating and maintenance costs.

The maintenance aspect of haul road design cannot be considered separate from the structural and functional design aspects since the two are mutually inclusive. Design and construction costs for the majority of haul roads represent a only a small proportion of the total operating and maintenance costs. Whilst it is possible to construct a mine haul road that requires no maintenance over its service life, this would be prohibitively expensive, as would the converse but rather in terms of operating and maintenance costs. An optimal functional design will include a certain amount and frequency of maintenance (watering, grading etc.) and thus maintenance can be planned, scheduled and optimised within the limits of required road performance and minimum vehicle operating and road maintenance costs. The major problem encountered when analysing maintenance requirements for haul roads is the subjective and localised nature of the problem; levels of functionality or serviceability being user- and site-specific. Whilst no guidelines exist concerning maintenance management and scheduling for specific levels of functionality, the cost implications thereof, both in terms of vehicle operating and road maintenance could be deduced from established cost models developed for public roads. It is however open to question whether such models extend to the operation of large haul trucks on surface mine haul roads.

Under these circumstances, there is a clearly defined need for research into the construction and management of flexible pavements for haul roads, appropriate for the wheel loads of vehicles now in use. Such research should not only address the structural problem, but in addition the functional and maintenance problems, thereby arriving at a total haul road design strategy combining mine life, mining layout, construction techniques, available material and road maintenance equipment with hauler choice to optimise a particular mining situation. Figure 1.1 summarises the three components of the total haul road design strategy.

The objective of producing specific and individual haul road designs must be based on a general design strategy that will enable the research to be applied to most surface mining operations. In this respect the design strategy must be portable such that the largest combination of operating conditions, traffic volumes and types and available construction materials are addressed, enabling the technique to be widely applied albeit based on a set of limiting or optimum design criteria.

The need for the development of a formal haul road design technique that encompasses both the pavement strength and operating performance aspects was confirmed through discussions with mining houses. The development of this design technique will lead to the potential reduction of haulage and road maintenance costs through the application of individual highly specific designs based on a general design and operation optimisation strategy.

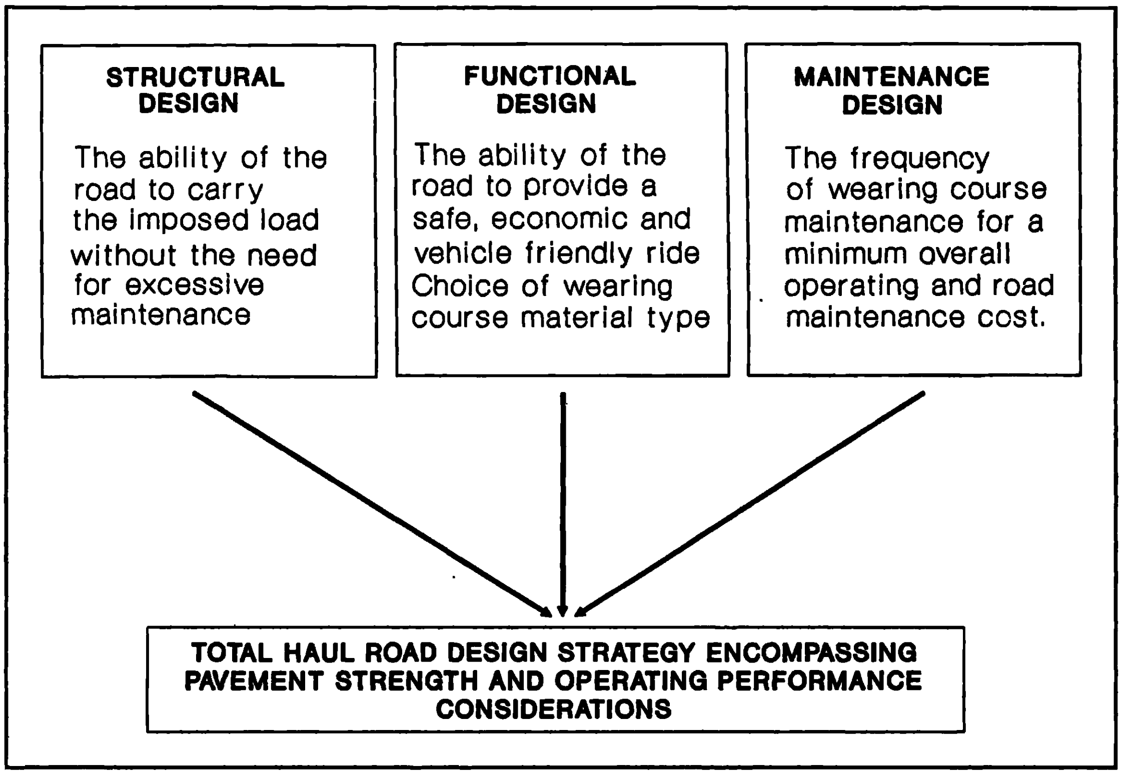

Figure 1.1 Elements of a Total Haul Road Design Strategy.

1.2 Problem Definition

Current haul road structural design techniques are purely empirical and based primarily on the previous experience of personnel assigned to pavement design, both in terms of the strength of the structure and the quality of the construction material. This has the potential for unwarranted expenditure for too thick a structure, or conversely, premature deformation leading to the need for excessive expenditure on maintenance. There is thus a need to develop a general and practical structural design method.

Similar empirical limitations exist in regard to haul road functional design, both in terms of quality requirements of the wearing course material and the associated level of functional performance. Poor functional performance can impact safety and economics through unwarranted expenditure on haulage, vehicle and road maintenance costs. There is thus a need to develop wearing course material selection guidelines for haul road design, based on road-user defined levels of functionality.

No guidelines exist concerning the management and scheduling of mine haul road maintenance, primarily due to subjective and localised nature of the problem. Poor maintenance management can impact economics through excessive expenditure on vehicle operating costs or road maintenance equipment operation. There is thus the need to develop a maintenance management system that minimises both vehicle operating and road maintenance cost elements.

1.3 Research Objectives

1.3.1 Objective statement

The primary objective of the research is the development of a haul road management technique that encompasses both pavement strength and operating performance considerations. Pavement strength and operating performance characteristics can be subdivided into the following design categories:

- Structural design
- Functional design
- Maintenance design

In developing a solution to the primary objective enumerated above, the following intermediate component research activities will be addressed within each design category.

1.3.2 Structural Design

The structural design concerns the ability of a haul road to carry the imposed loads without the need for excessive maintenance. The following activities are identified within this activity:

a. The analysis and quantification of the structural properties of existing pavements.

b. The prediction of structural performance through the use of analytical models.
c. The recommendation of a formal structural design procedure which encompasses traffic volumes and vehicle loads, climate and material properties.
d. The implementation and monitoring of the procedure.

1.3.3 Functional Design

Functional design aspects refer to the ability of the haul road to perform its function, i.e to provide an economic, safe and vehicle friendly ride. The selection of wearing course materials primarily controls the functional performance. The following activities are identified within this activity:

a. A survey of the performance of existing wearing course materials.
b. Determine the applicability of existing public road material selection guidelines for use in haul road functional design.
c. The recommendation of selected wearing course material to fulfil requirements.
d. The implementation and monitoring of the selection criteria.

1.3.4 Maintenance Design

The maintenance aspect of haul road design cannot be considered separate from the structural and functional design aspects since the two are mutually inclusive. Maintenance design concerns the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs. The following activities are identified within this activity:

a. Analysis of pavement deterioration rates and maintenance cost/road quality relationship.

b. Develop vehicle operating and pavement performance models.

c. Produce a maintenance management system for surface mine haul roads.

d. The implementation and monitoring of the management system.

1.4 Structure and Scope of Thesis

In developing a solution to the primary objective, the three elements of structural, functional and maintenance design are addressed in this thesis. The historical background to mine haul road design is presented in Chapter 2 together with a summary of the inherent deficiencies associated with the existing structural, functional and maintenance design methods. In addition to a summary of the current state of mine haul road design, current research concerning unpaved road design in the public domain is also presented where this has the potential for application in mine haul road design.

Following the identification of the deficiencies inherent in each design element, Chapter 3 presents the decision process behind the experimental design for the structural, functional and maintenance design elements. A discussion of the mine test site locations, testing and monitoring techniques follows, together with a summary of the chosen mine test site factors level combinations and data collation requirements for each design element.

Chapter 4 addresses the empirical analysis and quantification of existing pavement structural designs, following which Chapter 5 provides results of a mechanistic analysis of these same pavements. Through comparison of the empirically-designed and mechanistically-analysed pavement performance, the derivation of a mechanistic design procedure, incorporating limiting design criteria, effective elastic modulus selection and the recommended structural design, is given in Chapter 6. The recommended design procedure is applied in a comparative structural design case study in Chapter 7 following which Chapter 8 briefly summarises the main findings of the structural design research.

The functional design research component is introduced in Chapter 9 in which the development of a qualitative functional performance assessment methodology for mine haul roads is described. The results of a functional performance monitoring exercise are described in terms of the extent to which functionality requirements are satisfied by the wearing course materials currently in use. Chapter 10 concerns the statistical analysis of deterioration and maintenance effects and the development of a predictive model for defect score progression between maintenance cycles, together with statistical analysis of wearing course material parameters and individual defect scores to determine parameters implicated in each type of haul road defect. Chapter 11 introduces the methodology adopted in determining acceptability limits for mine haul road functionality, following which the results are analysed and acceptability limits and defect rankings deduced as a precursor to the assessment of established selection guidelines when applied to mine haul road functional design. The derivation and recommendation of wearing course material selection parameters for mine haul road construction is contained in Chapter 12, based on the identification, characterisation and ranking of defects as derived from the previous chapter.

The development of a mine haul road maintenance management system is described in Chapter 13 in which a road roughness progression model is developed, forming the core of the road roughness/maintenance frequency investigation. Roughness is assessed in terms of both rolling resistance, a subjectively derived roughness defect score and the equivalent quantitative IRI roughness. Correlations are established between each measuring system to enable meaningful comparison and ensure portability of the technique. Chapter 14 concerns the development of vehicle operating and road maintenance cost models for the prediction of fuel consumption, tyre cost, vehicle parts and labour cost and road maintenance cost variation with road roughness. These models are combined in a maintenance management system computer program to facilitate a systems analysis approach as described in Chapter 15. Details of the program input, computation and reporting phases are given prior to an evaluation of the results in terms of both established maintenance practices on mines and the financial implications of sub-optimal maintenance strategies.

Finally, Chapter 16 provides a summary of the conclusions reported for each design category analysed, together with the recommendations for further research identified during these investigations. In conclusion, an implementation strategy for the new haul road design and management techniques proposed in this thesis is outlined by means of which road-user cost benefits may be realised whilst further enhancing the applicability of the techniques developed.

1.5 Principal Findings of the Research

1.5.1 Structural Design

The optimal mechanistic structural design of a surface mine haul road embodied the determination of limiting structural design criteria, the recommendation of target effective elastic modulus values for the construction materials available and the placement of those materials such as to optimise their performance both as individual layers and over the entire structure. Structural performance was analysed in terms of minimum wearing course thickness and compaction and the limiting design criteria of vertical strain in the base, sub-base and sub-grade layers.

Two design criteria were proposed with which to assess the structural performance of mine haul roads, namely factor of safety (FOS) for the two uppermost layers and vertical elastic compressive strain for each layer below the top layer. It was found that the vertical strain criterion correlated well with the structural performance of the road and traffic volumes and that an upper limit of 2000 microstrain should be placed on layer strain values. The depth of influence at which load induced stresses are no longer felt was identified at approximately 3000mm pavement depth. With regard to the FOS design criteria for the upper layers, it was concluded that this criteria was not applicable to haul road design. In the absence of any definitive criterion, a 200mm layer of compacted (95-98% Mod. AASHTO) good quality gravel was recommended.

The selection of target effective elastic modulus values for typical construction materials incorporated an analysis of various material laboratory parameters. This approach facilitates the practical application of the method on the mines. A modulus range of 150-200MPa was proposed for G4-G6 gravels when used as a wearing course and 75-100MPa for the same material when used as a base or sub-base layer. Values for the modulus of the in-situ sub-grade material were found to be very much site and material specific and the use of Dynamic Cone Penetrometer (DCP) derived California Bearing Ratio (CBR) values in conjunction with published data was recommended as the most tractable approach in ascertaining suitable modulus values for this material.

Recommendations regarding the structural design of surface mine haul roads were centred on the inclusion of a dumprock layer within the structure. The optimal location of this layer was found to be immediately below the wearing course layer. Using this approach, a reduced structural thickness was realised without the attendant deformation and reduction in structural performance level that would otherwise be evident without a rock layer. In a comparative study of the hitherto empirical CBR cover curve design methodology for mine haul roads with the new mechanistically designed optimal equivalent, the proposed optimal design provided an improved structural response to the applied loads and, in addition, did not contravene any of the proposed limiting design criteria. In terms of construction costs, a 15% cost saving per kilometre was realised over the CBR based design by using the mechanistically derived optimal design.

1.5.2 Functional Design

Functional design aspects refer to the ability of the haul road to perform its function, i.e to provide an economic, safe and vehicle friendly ride. This is dictated to a large degree through the choice, application and maintenance of wearing course materials.

Major haul road functional defects encountered were dustiness, loose material, fixed and loose stoniness and crocodile cracking. A statistical analysis of deterioration and maintenance effects associated with these key defects revealed that wearing course material properties, especially grading and plasticity parameters, together with traffic volume, could be used to adequately model the functional performance of these key defects. The applicability of the model is however limited by the relatively small inference space of the data.

Acceptability criteria for haul road functionality were developed with which to categorise the various functional defects analysed. It was concluded from the ranking exercise that wet skid resistance, dustiness, erodibility and ravelling and corrugating are critical defects which control the functionality of mine haul roads. A revised range of material selection parameters was derived based on the road-user preference for much reduced wet slipperiness, dustiness and dry skid resistance defects. The specification included the parameters of shrinkage product and grading coefficient and limits of 85-200 and 20-35 respectively were proposed. In addition, from analysis of the range of material property parameters assessed and their association with the functional defects analysed, parameter ranges were additionally specified for density, dust ratio, Atterberg limits, CBR and maximum particle size.

1.5.3 Maintenance Design

The maintenance aspect of haul road design cannot be considered separate from the structural and functional design aspects since the two are mutually inclusive. The proposed mine haul road maintenance management system (MMS) was developed from established MMS applied in the public domain, together with specific modifications which reflect the requirements of mine haul road-users.

A qualitative road roughness evaluation technique was developed as a precursor to the development of a model for roughness progression. Increasing traffic volume, grading coefficient and shrinkage product were all associated with an increasing rate of roughness progression whilst increasing CBR and plasticity index were associated with a decreasing progression. In addition, rolling resistance was assessed and results compared to established models for light commercial vehicles. The model derived for mine haul road roughness variation with International Roughness Index (IRI) was found to be broadly similar to models developed for paved and unpaved public roads, albeit with a non-linear rate of change of rolling resistance per unit IRI.

The second element of a MMS for mine haul roads was based on models of the variation of vehicle operating and road maintenance costs with road roughness. The fuel consumption model development was based on the simulation of typical coal haulage trucks used by the mines. With regard to the tyre, vehicle maintenance parts and maintenance labour models developed, data limitations precluded the development of statistically robust models. Existing models developed for commercial trucks in the public domain were used as a basis for the development of mine haul truck models. Although the parameter ranges bore little resemblance to those of mine haul trucks, when coupled with a hypothesis of the influence road roughness and geometry on these cost components, a basic model was developed in each case.

A MMS model program for mine haul roads was developed for the evaluation of alternative maintenance intervals and the associated effect on total operating costs, comprising vehicle operating and road maintenance cost elements. An evaluation of the total cost variation with maintenance interval enabled the optimum maintenance interval to be determined, both on a minimum total cost basis and in terms of maintenance equipment available operating hours. Actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to increased maintenance interval on lightly trafficked roads. Sub-optimal maintenance strategies were seen to be associated with excessive expenditure on total road-user costs. It was concluded that the adoption of the MMS model program for mine haul roads has the potential to generate significant cost benefits when used dynamically in conjunction with production planning to optimise mine haul road maintenance activities.

CHAPTER 2

CURRENT STATE OF MINE HAUL ROAD MANAGEMENT

2.1 Introduction

The historical background to mine haul road structural, functional and maintenance design is presented following which the current state is reviewed and inherent deficiencies identified. A summary of research pertaining to the design of unpaved roads in the public domain is presented where this work has the potential for application in mine haul road management. Through the identification of the deficiencies that exist in current haul road design techniques and the recommendation of strategies employed in the design of unpaved roads in the public domain, the basis for the experimental design is established.

2.2 Current State of Structural Design

In an attempt to obtain satisfactory service over a road's design life, pavement design models can be used to predict performance over a wide range of traffic loads and road structural designs. Pavement structural design is the process of developing the most economical combination of pavement layers (in relation to both thickness and type of materials available) that is commensurate with the in-situ material and traffic to be carried over the design life.

The load bearing capacity of a soil is directly related to its shear strength, given by the Mohr-Coulomb equation. Tyre loadings of large haul trucks generally exceed the bearing capacity of most roadbed materials (at their normal in-situ moisture content) and thus anything less consolidated than soft rock will not provide a stable base for the haul road and other materials will need to be placed over the sub-grade to protect it and adequately support the road structure and traffic.

Early haul road design techniques consisted of placing several layers of granular material over the in-situ material and as deterioration occurred, more layers were added. These reactionary methods were quickly rendered obsolete when the CBR design technique was introduced as a method for the structural design of mine haul roads (Kaufman and Ault, 1977). The CBR technique has numerous disadvantages when applied to the design of haul roads, specifically the limited pavement behaviour data-base from which the method and its derivatives (Goswami and Bhasin, 1986, Gokhale et al, 1986) are generated (Porter, 1949, Otte, 1979) and the limitations of the Boussinesq semi-infinite single layer elastic theory. Modern multi-layer structures, often including stabilised layers may not amenable to a reliable CBR based design technique. Otte (1979) further notes the inapplicability of the method for the design of pavements carrying heavy traffic, except in the case where untreated material is used in conjunction with a thin (or no) surface layer. However, it remains to determine the extent of over- or under-design associated with this method when applied to the structural design of mine haul roads. Other techniques, also empirically derived and applied to the design of flexible airport pavements (Corps of Engineers, 1956, Brown and Rice, 1971 and Asphalt Institute, 1973) form a suitable point of departure for the development of a structural design methodology for mine haul roads, specifically with regard to permissible stress and strains in sub-grade materials.

The use of the Dynamic Cone Penetrometer (DCP) in determining the in-situ shear resistance of material has enabled predictive models of pavement performance to be developed for thin surfaced unbound gravel flexible road pavements (Kleyn, 1975, Kleyn et al, 1982). Correlation of DCP results to the CBR has been established, as well as to the 7-day soaked unconfined compressive strength (UCS) of lightly cemented materials (UCS<3 000kPa), as discussed by Kleyn (1984) and De Beer et al (1988). In this respect the DCP technique may provide a suitable extension of the CBR design technique, specifically regarding the measurement of pavement CBR values. However, a DCP analysis alone is insufficient to fully characterise the response of a haul road to the applied loads. To supplement and validate the DCP approach a means of assessing the stresses and strains deeper in the pavement is required. However, the DCP can be applied in determining pavement layer strengths as a precursor to a multi-layer mechanistic analyses.

When considering the performance of multi-layer structures, the mechanistic design approach is more appropriate. Analysis of pavement response by simulation, as opposed to the empirical CBR approach, requires that the effective elastic moduli and stress sensitivity of the materials comprising the pavement structure be known. This is most readily achieved by back-calculation from depth deflection profiles. Adopting a mechanistic approach enables the balance of the design, or the change in strength of the pavement layers with depth, to be analysed. The extent to which this phenomenon manifests itself depends on the strength and composition of the various layers to the traffic load. The concept of a balanced pavement can be analysed mechanistically through consideration of individual layer strengths, resulting in an overall balanced design in which each layer is working at maximum efficiency without being overstressed. Implicit in this approach is an understanding of the stress sensitivity behaviour of the pavement structural layers and the limiting design criteria required to ensure adequate structural performance. Stress sensitivity has been analysed by Maree et al (1982) in which crushed stone base and cohesive sub-grade layers were tested at load levels up to 100 kN. Other limiting design criteria, including factor of safety (FOS) and vertical compressive strain have been discussed and applied in road and airfield design (Maree, 1978, Corps of Engineers, 1956, Brown and Rice, 1971 and Aphalt Institute, 1973) and may be amenable to adoption in the design of mine haul roads.

2.3 Current State of Functional Design

Compacted natural gravel and crushed stone and gravel mixtures have been widely used in strip coal mines for haul road construction, especially for base and wearing course layers. The functional design of a haul road is the process of selecting the most appropriate wearing course natural gravel or crushed stone and gravel mixtures that are commensurate with safety, operational, environmental and economic considerations.

Most mines use cost per ton material moved as an immediate measure of haulage efficiency and in general terms the contribution of haulage costs to total mining working costs may vary between 10-20%. When considering those factors influencing the cost per ton hauled and the truck/road interaction, those with most significant impact on the functional performance of the road are rolling resistance and roughness. These two factors can have a significant impact on both immediate and long term performance and cost. Most off-highway vehicle manufacturers are able to carry out vehicle simulations to determine the effect of rolling resistance on productivity for a specific machine and route and the results of such analyses show increasing costs and falling productivity associated with increased rolling resistance (Monroe, 1990). Recent work (Paige-Green, 1989) has illustrated that the choice of wearing course material is critical to optimal functional performance, not only in terms of rolling resistance and roughness, but also in terms of numerous other defects which, in combination, will greatly affect user costs or the cost per ton hauled.

Kaufman and Ault (1977) provide an early insight into haul road functionality through a limited consideration of general road performance. They stated that the primary characteristics to be considered were road adhesion and rolling resistance and the most practical construction materials recognised were asphaltic concrete, crushed stone or gravel and stabilised earth. The concept of functionality was not specifically introduced but rather alluded to in terms of some of the defects reported with these various construction materials. Large rocks were seen to lead to excessive tyre replacement costs, whilst excessive fines or poor compaction led to dust problems. The impact of the dust problem on haulage operations was related to excessive vehicle maintenance costs and reduced visibility. Dust control by watering was associated with adhesion problems and erosion of the road surface, especially where poorly compacted or unstabilised earth was employed. In conclusion, they recommended crushed stone or good quality natural gravel as wearing course materials, together with specifications for gradation and Atterberg limits. An abundance of information exists describing good engineering practice in the layout and geometry of mine haul roads (Dubni, 1972, Chironis, 1978, Fung, 1981, Atkinson and Walton, 1986, Collins, Fytas and Singhal, 1986 and Taylor and Hurry, 1987) and it is beyond the scope of this work to summarise and comment on this aspect of haul road construction; suffice to say that optimal functional performance can only be achieved when sound geometric design principles are applied in conjunction with optimal wearing course material selection.

Off-highway vehicles were until recently considered "rugged" and the quality and condition of a mine haul road was not a sensitive factor in the application of surface mine transport. Recently, due to the increasing size and variation in the design of haul trucks and the changing economic climate (altering the balance in the trade off between haul route quality, productivity and haul truck maintenance costs), more attention has been given to these factors. Work in Australia in 1982 (Granot, Marshall and Dickenson, 1982) concluded that most structural damage to trucks took place at loading or in-pit dumping points. However, the lengths of these sections in comparison to the length of the total haul route is not clearly stated, thus precise contributions to overall damage cannot be separated for each segment of the haul. Kondo (1984) suggests that haul trucks are more sensitive to haul road conditions when travelling at speed than is a standard vehicle with a more responsive suspension. This has been attributed in part to the generation of harmonics in the vehicle frame. Combined with high impact stresses produced by irregularities in the road, these vibrations can lead to metal fatigue, often manifest as failure of the goose neck connections on bottom dump trucks. More recent work by Deslandes and Marshall (1986) recognised haul road surface quality as being an important factor influencing structural fatigue damage of haul truck frames. The trade-off between extremely smooth running surfaces and haul truck reliability was assessed, based on work by Kondo (1984). Recommendations were made with regard to road maintenance and construction practices generally in geometric terms, but also including reference to the reduction of road surface roughness where laden travel occurs and at bends and intersections. Deslandes and Dickerson (1989) introduced the concept of twisting or racking of a vehicle frame as being a better measure of haul truck fatigue damage. Twisting occurs when one of the haul truck tyre contact points does not lie in the plane of contact of the following wheel. Work by Kondo (1984) and Structural Dynamic Research Corporation (1977) supports the notion of twist induced fatigue being a limiting design criteria for large haul trucks as opposed to road roughness alone.

2.3.1 Wearing Course Materials

Work by the Kaufman and Ault (1977) concerning the choice of wearing course materials highlighted the most appropriate material characteristic design parameters, namely rolling resistance and adhesion. It is suggested that road adhesion is the primary characteristic to be considered and asphaltic concrete, crushed stone or gravel and stabilised earth are the most practical construction materials. More recent work by Taylor and Hurry (1987) echoes these findings in most respects although the comment is made that stabilised wearing courses are not amenable to maintenance and should be avoided. In addition, from a purely economic standpoint, asphaltic concretes are considered inappropriate except for relatively short permanent high traffic areas as dust spillage makes the surface slippery. Test work has been conducted on an opencast mine in South Africa to determine the feasibility and performance of concrete paving blocks as a running surface (Michau and Wilson, 1992). Estimation of maintenance benefits cited are dubious and analysis of the test section performance is incomplete. Other advantages cited by Fung (1981) for paving include the reduction of dust during dry weather and the excellent drainage provided in wet weather. Spillage, if not quickly and efficiently removed can build upon paved surfaces and reduce ride quality considerably. However, when a grader is used to continually smooth over a crushed stone wearing course, the advantages of paving are unwarranted.

The most common wearing course material for haul roads remains compacted gravel or gravel and crushed stone mixtures. In addition to their low rolling resistance and high coefficient of adhesion, their greatest advantage over other wearing course materials is that roadway surfaces can be constructed rapidly and at relatively low cost. As with structural designs, if local mine material can be used for construction, the costs are all the more favourable. This cost advantage is, however, not apparent in the long term if the characteristics of the wearing course material result in sub-optimal functional performance.

Wearing course gravel characteristics have been described additionally by Fung (1981), M^{c}Innes (1982), Atkinson and Walton (1986) and Taylor and Hurry (1987). These specify in general a good quality natural gravel or crushed stone. M^{c}Innes (1982) presented a comparison of conventional and off-highway wearing course requirements which is presented in Table 2.1, based on the Standard Association of Australia (NAASRA,1974) specifications. M^{c}Innes comments that the latter specifications are not entirely suitable for haul road wearing course material selection and proposes modifications and additions to selection guidelines. Some discrepancy exists relating to material gradation and only Kaufman and Ault (1977), M^{c}Innes (1982) and Fung (1981) refer to consistency limits, the later being drawn directly from the American Association of State Highway and Transportation Officials (AASHTO) classification scheme.

Whilst these limited characteristics broadly define the suitability of materials used for

Table 2.1 Haul Road Wearing Course Material Selection Guidelines (following M^{c}Innes, 1982)

SELECTION FACTOR	HAUL ROAD REQUIREMENTS
Surface wear resistance	Gravel sized aggregate exposed to loading and abrasion, should not disintegrate unduly under traffic.
Shear strength	Should not rut at moisture condition resulting after heavy rain, this is usually wet of optimum.
Stiffness	Some surface deflection allowable, permanent deformation should be avoided.
Dry strength	Must withstand traffic action over entire surface and surface must bind to avoid dust problems.
Erosion resistance	Clay fractions should not be rapidly dispersed and thus easily removed.
Compaction requirements to achieve maximum density	Materials should preferably compact without close control over moisture content.

wearing course construction, they are generally lacking in their ability to predict the functional performance of haul roads. Numerous material selection guidelines for unpaved public roads have been developed, including those of Olmstead (Wooltorton, 1954), the Natal Roads Department (Natal Provincial Authority, 1961) and TRH20 (Committee of State Road Authorities, 1990) which are based on performance or defect related specifications. In the TRH20 document, selection guidelines are also presented for unpaved haul roads, however,it remains to be seen whether or not these guidelines are appropriate for mine haul roads. Appendix A contains a summary of existing wearing course material selection guidelines under review and Figure 2.1 shows typical selection guidelines in terms of TRH20 specifications. The suitability of these guidelines needs to be investigated in terms of the required functionality of the haul road and the performance of existing pavements. As a first step in isolating typical haul road functional performance defects it is necessary to review ideal wearing course requirements.

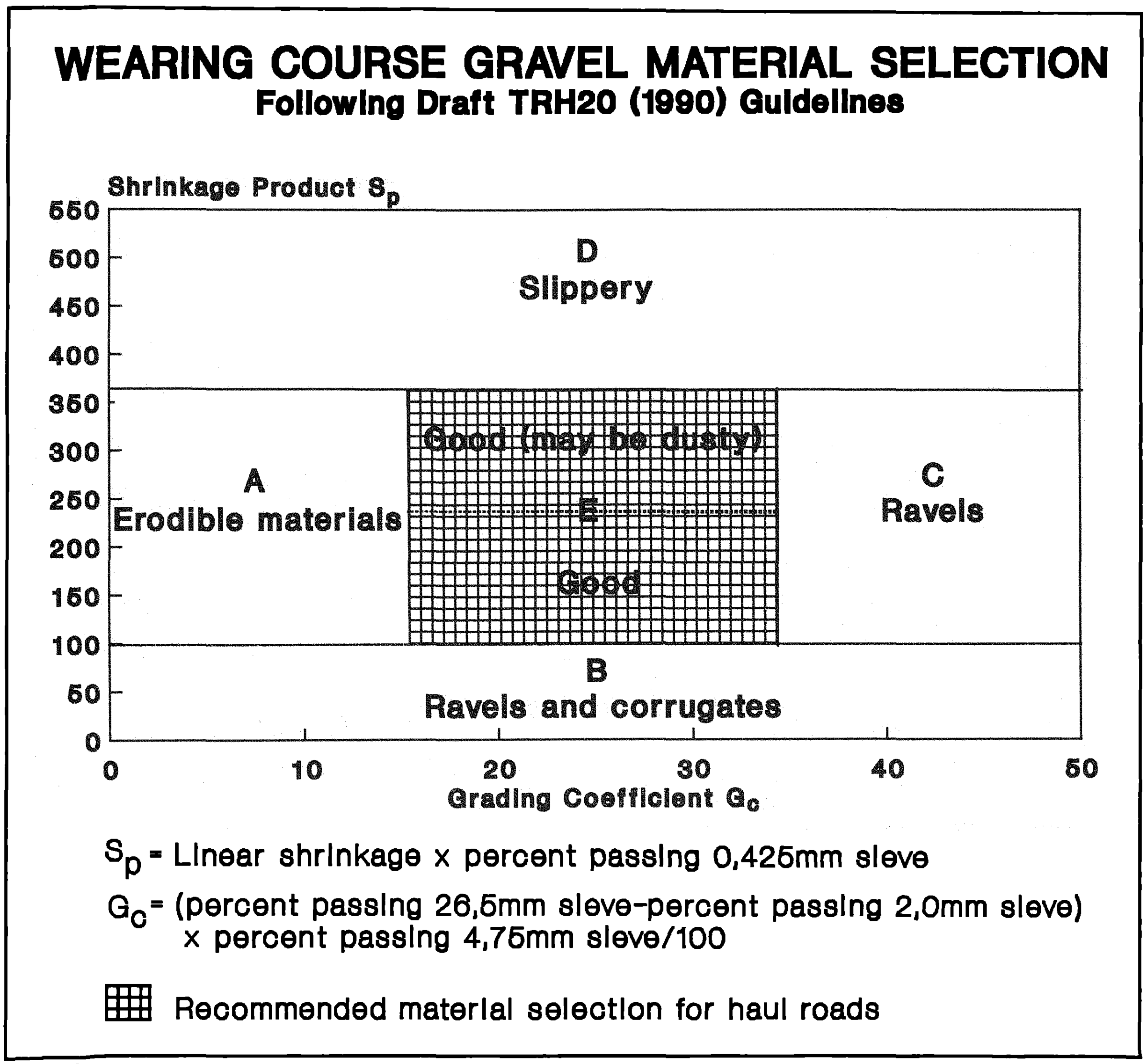

Figure 2.1 Wearing Course Gravel Material Selection Guidelines (after CSRA, 1990)

2.3.2 Ideal Wearing Course Requirements

Whilst immediate measures are useful to a mine in assessing short term road functional performance, the definitive economic analysis of haul road functionality is based on the comparison of the benefits and costs of providing other alternatives. Benefits are seen as overall cost savings through increased productivity and reduced fuel, tyre and maintenance costs. Improved functional performance implies a reduction in pavement defects and since functional performance is based almost entirely on qualitative measure, it is useful to review typical unpaved road defects.

M^{c}Innes (1982) introduced the concept of wearing course requirements in terms of modifications to the established NAASRA (1974) selection guidelines in which a number of ideal requirements were alluded to. Building on and updating this approach, an ideal wearing course for mine haul road construction can also be considered from the point of view of public unpaved road requirements. Netterberg (1985) and Paige-Green (1989) proposed the following requirements;

- The ability to provide a safe and vehicle friendly ride without the need for excessive maintenance.
- Adequate trafficability under wet and dry conditions.
- The ability to shed water without excessive erosion.
- Resistance to the abrasive action of traffic.
- Freedom from excessive dust in dry weather.
- Freedom from excessive slipperiness in wet weather.
- Low cost and ease of maintenance.

The relative importance of wearing course requirements for unpaved public roads was also categorised by Paige-Green (1989) in terms of service, safety, comfort and total costs. The limited literature available pertaining to mine haul road functionality (USBM, 1981) tends to echo the general categorisation presented by Paige-Green in Table 2.2, although comfort may be replaced by the concept of vehicle-friendly when used in conjunction with mine haul roads. It is evident that the relative importance of the various characteristics comprising overall functional performance need to be assessed as they apply to mining operations. The effect of haul road functional performance and maintenance on mine economics and safety is not well defined at present. However, it is clear that a strong relationship exists between road structural and functional performance and safe, economically optimal mining operations.

For existing operations, which may not have optimally designed and maintained systems, the problem of identifying existing deficiencies, quantifying their impact and assigning priorities within the constraints imposed by limited capital and manpower is problematic. Assessing the impact of various haul road functional deficiencies in order to identify the safety and economic benefits of taking corrective actions such as more frequent maintenance, regravelling or betterment is hampered by the lack of a problem solving methodology which can address the complex interactions of various components in a haulage system. This is reflected in the fact that most surface mine operators agree good roads are desirable, but find it difficult to translate this into proposed betterment activities.

A safe and vehicle friendly ride is important both from the point of view of public and mine roads. Factors affecting roughness are corrugations, stoniness, potholes and surface erosion.

Table 2.2 Relative Importance of Wearing Course Requirements for Public Roads (after Paige-Green, 1989)

Requirement	Service	Safety	Comfort	Total costs	Material requirements
Smooth ride: ***Roughness***	C	B	B	A	Good grading, adequate cohesion and strength
Stability	A	B	B	A	Good grading, strength and density
Water shedding:					
Erosion	B	B	A	A	Adequate cohesion
Trafficability	A	B	B	A	Good grading, strength and density
Resistance to abrasion:					
Loose material	C	A	B	B	High density and cohesion
Gravel loss	A	C	B	A	High density and cohesion
Rutting	B	B	B	B	High density and cohesion
Freedom from dust	C	A	A	C	Adequate plasticity index
Not slippery	C	A	C	C	Good grading, not too plastic
Ease of maintenance	B	B	B	A	Little oversize
Notes: A - Very important B - Important C - Unimportant					

Stability is more a function of structural design, inadequate structural design will lead to potholes, rutting and general deformation together with reduced wet weather trafficability. The ability of the road to shed water is also important, especially when considered in conjunction with the shallow (1%-2%) crossfall across 12m-13m of road width. Water accumulations will result in potholes and depressions, whilst poor choice of materials or excessive cross-fall may lead to erosion channels forming in the road, both ultimately affecting riding quality.

The abrasive action of traffic results in the development of ruts, generation of loose material and an overall material loss with time, all of which necessitate regravelling. Dust is undesirable primarily from the safety aspect and is associated with excessive fine material or the generation of such material due to the action of traffic. A suitably well graded material will also reduce slipperiness of the road, both in wet and dry weather.

2.4 Current State of Maintenance Management

The maintenance of mine haul roads is an integral component of both the structural and functional designs. Ideally, the maintenance strategy adopted should be the one that results in the minimum total cost since, in the case of mine haul roads (as opposed to unpaved roads in the public domain), the agency controlling the haul road network is also affected by user operating costs. However, the management and scheduling of mine haul road maintenance has not been widely reported in the literature, primarily due to the subjective and localised nature of operator experience and required functionality levels. In most cases (Granot et al, 1982, Hawkey, 1982, Hatch, 1982, Taylor and Hurry, 1987 and Hustralid and Kuchta, 1995) comment is restricted to the various functions comprising maintenance, as opposed to the management of maintenance to minimise overall costs.

Several authors have attempted to investigate the effect of road roughness on the structural reliability of haul trucks, the implicit assumption being that any improvement in road roughness will have considerable benefit in terms of reduced vehicle down-time. The elements comprising total vehicle operating costs were not identified or quantified and as such the utility of this approach in reducing total vehicle operating costs is not clear.

Deslandes and Dickerson (1989) present a mine haul road maintenance evaluation technique as a basis for maintenance scheduling, correlated with likely structural fatigue induced in the haul vehicle sub-frame due to haul road roughness. Haul trucks were instrumented with strain gauges and road roughness was indirectly assessed from consideration of the measured stress-histories over the route. Although the technique claims to advance cost-effective maintenance, no measure is made of the impact of revised maintenance strategies on vehicle operating or road maintenance costs. A similar concept was adopted Kondo (1984) in which laser profiling of the haul road as opposed to vehicle mounted strain gauges were employed. The objectives of the work were primarily to identify the effect of road roughness on the vehicle sub-frame and chassis and did not assess as such the impact of roughness on vehicle operating costs. A classification system was developed based on the International Standards Organisation TC108 system by adding two additional classes. Roughness was assessed using a laser profilometer and the results reported as power spectral densities and associated counts per metre of road. Although haul road condition reports are gathered and classified according to this system, no details are given concerning correlation of the (subjective) assessments to power spectral densities and frequencies. Again, no substantiating vehicle operating costs are reported. These omissions limit the utility of the work with regard to optimising road maintenance strategies.

Although conflicting reports exist in literature as to the exact contribution of the many parameters affecting rolling resistance, it is widely accepted that the influence on vehicle fuel consumption is significant (Shear et al, 1986). For medium-sized passenger cars on paved public roads, a 10% reduction in rolling resistance can improve vehicle fuel consumption by 1-3%, depending on the mode of operation of the vehicle. Roughness may significantly affect the rolling resistance of a vehicle but the exact contribution is equivocal, researchers both proving (Bester (1984) and Watanatada (1981)) and disproving (Morosiuk and Abaynayaka (1982) and Zaniewski et al (1982)) the existance of any contribution. This work was limited to the study of passenger cars and commercial trucks on mostly paved public roads.

Haul truck manufacturers limit comments on road roughness to equivalent rolling resistance in which mine roads are categorised according to a short description of the road surface type, unpaved roads varying from between 3,5% (dry, unpaved plain road) to 12% (loose material) (Komatsu, 1993). Caterpillar (1990) provide slightly more road surface condition information enabling a more informed choice to be made regarding the associated equivalent rolling resistance. However, the information presented in Table 2.3 is nevertheless subject to differing interpretation and does not fully address the contributory components of road roughness.

Table 2.3 Typical Rolling Resistance Factors (after Caterpillar, 1990)

Road Category	**Haul Road Description**	**Rolling Resistance**	
		kg/t	**Equivalent percentage grade (%)**
I	Hard, smooth, stabilised surface without penetration under load, watered and maintained.	20	2
II	Firm, smooth rolling roadway with dirt or light surfacing, flexing slightly under load or undulating, maintained fairly regularly and watered.	32,5	3
III	Dirt roadway, rutted, flexing under load, little or no maintenance and watering, 25-50mm tyre penetration.	50	5
IV	Rutted dirt roadway, soft, no maintenance, no stabilisation, tyre penetration 100-150mm.	75	7,5

NOTES
Equivalent rolling resistance presented in terms of additional vehicle mass (kg/t GVM) or as additional grade of road. Values may vary with tyre type, pressure, flexing and temperature.

Vehicle simulation packages enable the effect of increased rolling resistance on vehicle operating costs to be assessed, but only from the limited perspective of fuel cost and production losses (Caterpillar, 1993). Collins et al (1986) and Monroe (1990) present the results of specific simulations which (for the particular haul geometry and production statistics employed) indicate that for each percentage increase in rolling resistance, fuel costs increase by 8% up to a rolling resistance of 5% and by 32% for rolling resistances in excess of 5%. Productivity falls by approximately 5,7% for each percentage increase in rolling resistance. Whilst the simulation technique is useful in assessing the cost implications of improved haul road functionality, correlation of rolling resistance to the components of haul road roughness (derived from a subjective assessment) or a profilometer assessment of roughness is still required to enable the subjective assessment of roughness to be translated into fuel cost savings. Hudson (1981) comments that the subjective assessment approach has a number of shortcomings but in general the benefits from it being a practical, inexpensive and stable technique of evaluating road roughness warrants its adoption. Haul road roughness may be attributed to a number of critical defects namely potholing, corrugation, rutting, loose material and fixed stoniness and a subjective evaluation of roughness should include a degree and extent description of each defect. In this manner a correlation between measured and subjectively evaluated roughness can be established as a basis for road roughness and vehicle operating cost modelling.

Mine haul road maintenance strategies are not widely reported in the literature, only Long (1968) suggesting that adequate serviceability (functionality) can be achieved by the use of one motor grader (and water car) for every 45 000tkm of daily haulage. Collins et al (1986) suggest grading be accompanied by watering to reduce dust generation problems. A watering rate of between 1 and 2,5l/m^2/hour is recommended, dependant on traffic volume, wearing course, humidity and precipitation. The United States Bureau of Mines Minerals Health and Safety Technology Division (USBM, 1981) in their report on mine haul road safety hazards confirm these specifications, but without a clear statement as to what activities comprise road maintenance. In addition to the lack of unanimous objectives in applying maintenance, the definition of maintenance as applied to mine haul roads is not well defined. Paterson (1987) presented a summary of maintenance activities on unpaved public roads, sub-divided into the categories of routine maintenance, resurfacing, rehabilitation and betterment, as part of a coherent terminology for road expenditures. The routine maintenance category and associated activities and effects is adopted to describe the various maintenance activities envisaged within a maintenance management system (MMS) and is summarised in Table 2.4.

Routine maintenance is carried out on mine haul roads almost daily, depending on the functionality of the road (degree and extent of a defect or combination of defects) and the traffic volume. The principal goals are;

- To restore the road functionality to a level adequate for efficient vehicle travel with the aim of augmenting productivity and minimising maintenance costs,
- to conserve the integrity of the road wearing course by returning or redistributing the gravel surface.

Optimising maintenance schedules consists of determining the most opportune frequency at which to maintain a road such that vehicle operating and road maintenance costs are minimised over the whole road network, as illustrated in Figure 2.2. From the functional performance assessment (Thompson and Visser, 1995) it was found that maintenance intervals were closely associated with traffic volumes, operators electing to forgo maintenance on some sections of a road network in favour of others. This implies an implicit recognition of the need to optimise limited maintenance resources to provide the greatest benefit in terms of total maintenance and vehicle operating costs. This optimisation approach is inherent in the structure of existing MMS developed for the public sector and as such, may be used initially to investigate the suitability of MMS when applied to mine haul roads. Two elements form the basis of the economic evaluation, namely pavement functional performance and vehicle operating and road maintenance costs. Existing MMS

Table 2.4 Maintenance Categories and Activities for Mine Haul Roads.

Mode	Activity	Effect
Routine Maintenance	Spot regravelling Drainage and verge maintenance Dragging Shallow blading Dust control/watering	Fill potholes and small depressions, reduce roughness, exclude water. Reduce erosion and material loss, improve roadside drainage. Redistribute surface gravel. Redistribute surface gravel, fill minor depressions and ruts. Reduces loss of binder and generation of dust.
Resurfacing	Full regravelling Deep blading	Restore thickness of wearing course. Reprofile road and reduce roughness. Remix wearing course material.
Rehabilitation	Rip, regravel, recompact	Improve, strengthen or salvage deficient pavement.
Betterment	Rehabilitation and geometric improvement	Improve geometric alignment and structural strength.

are based on the optimisation of these elements.

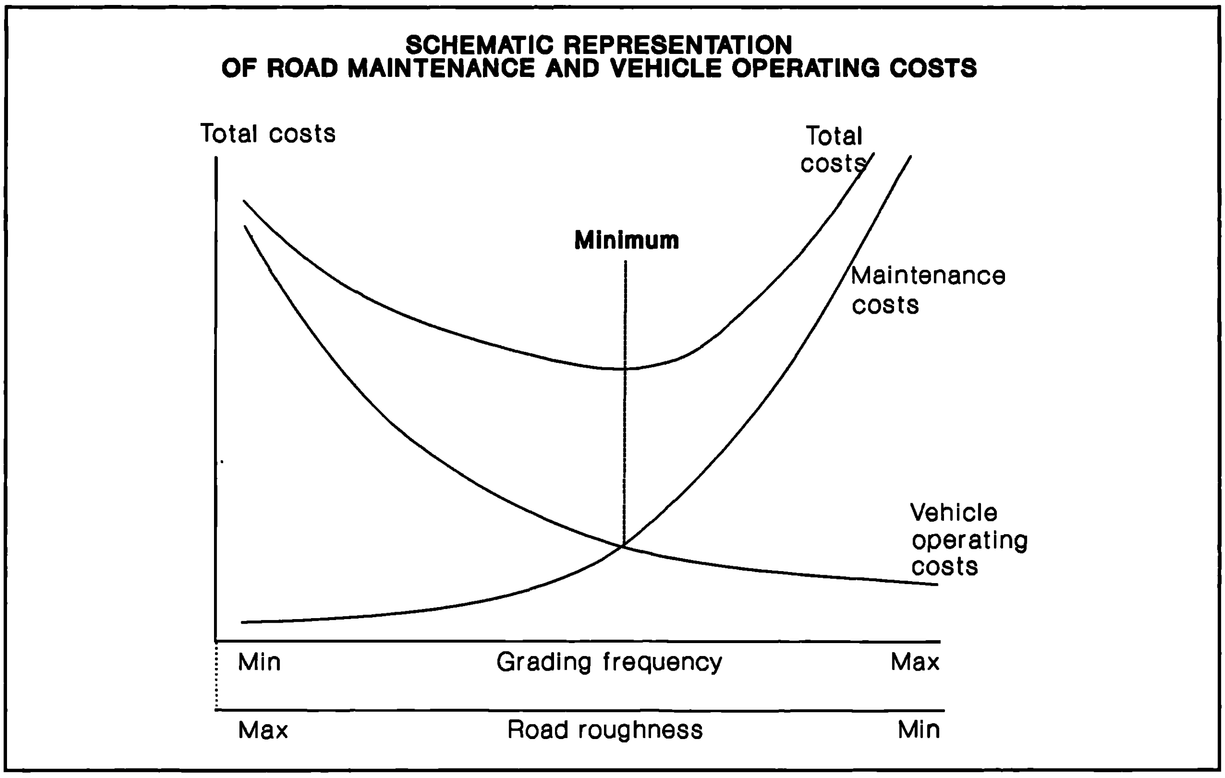

Figure 2.2 Minimisation of road maintenance and vehicle operating costs.

Existing MMS have been derived and applied in the assessment of alternative design, construction and maintenance strategies for both paved and unpaved roads, as described by Haas and Hudson (1978). The World Bank Highway Design and Maintenance Standards Study developed one such model which is described by Watanatada (1981) and summarised by Paterson (1987). In essence, the model is designed for a network, as opposed to a single road analysis of policies and standards. For a number of road segments of differing functional and traffic volume characteristics, together with user specified strategies, the model computes;

(i) Traffic volumes over the analysis period (as specified)
(ii) The change in road functionality (as predicted)
(iii) The maintenance quantities as required by the particular strategy
(iv) The vehicle operating costs (by prediction)
(v) Total costs and quantities (including exogenous specified benefits)

Finally, the model computes a number of economic criteria for assessing the cost implications and maintenance schedules of the network and individual links. Economic efficiency suggests that tradeoffs should be made between the cost of alternate strategies and the economic return that is derived from lower total transportation costs. In this manner, the maintenance management programme adopted and the associated budget requirements, should be economically justifiable. Figure 2.3 illustrates the model flow chart. This model includes road construction costs as a component of total costs. When analysing optimum maintenance strategies to be applied to an established mine haul road, road construction costs need not be considered since these will be the same for all alternative strategies.

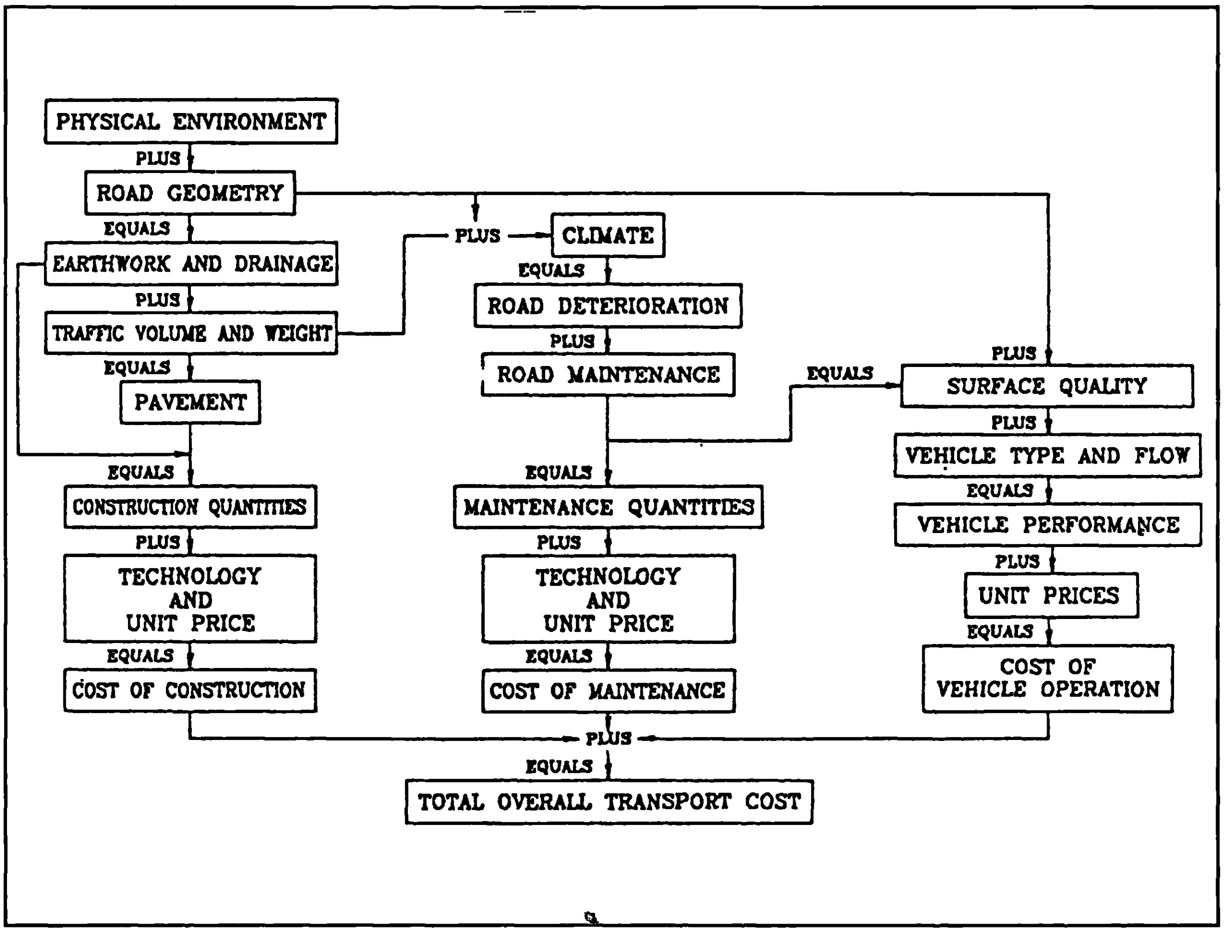

Figure 2.3 Flow Chart of the World Bank Model for Transport Cost (after Butler et al, 1979)

Visser (1981) presented a maintenance and design system for unpaved roads which enabled alternative regravelling and blading strategies to be assessed within a system of constraints related to road purpose and technical limitations. The basis of the evaluation was total transport costs, consisting of vehicle operating and road maintenance costs. A simplified flow-chart for the model is presented in Figure 2.4. In contrast to unpaved public roads, mine haul roads are subject to more frequent routine maintenance and, since roughness is the major controllable factor affecting vehicle operating costs (Committee of State Road Authorities, 1990), the most tractable approach to maintenance design and cost optimisation (through a reduction in vehicle operating cost associated with managed maintenance) thus lies initially in optimising routine maintenance activities as opposed to optimisation of design, blading and regravelling activities over a much larger time scale. Whilst the latter approach, when coupled with construction costs, would make a valid contribution to optimising total haulage costs (as illustrated by Perkins (1990) for the case of forestry roads), with reference to the development of a total haul road design strategy and more specifically a maintenance management system, it falls outside the scope of this research.

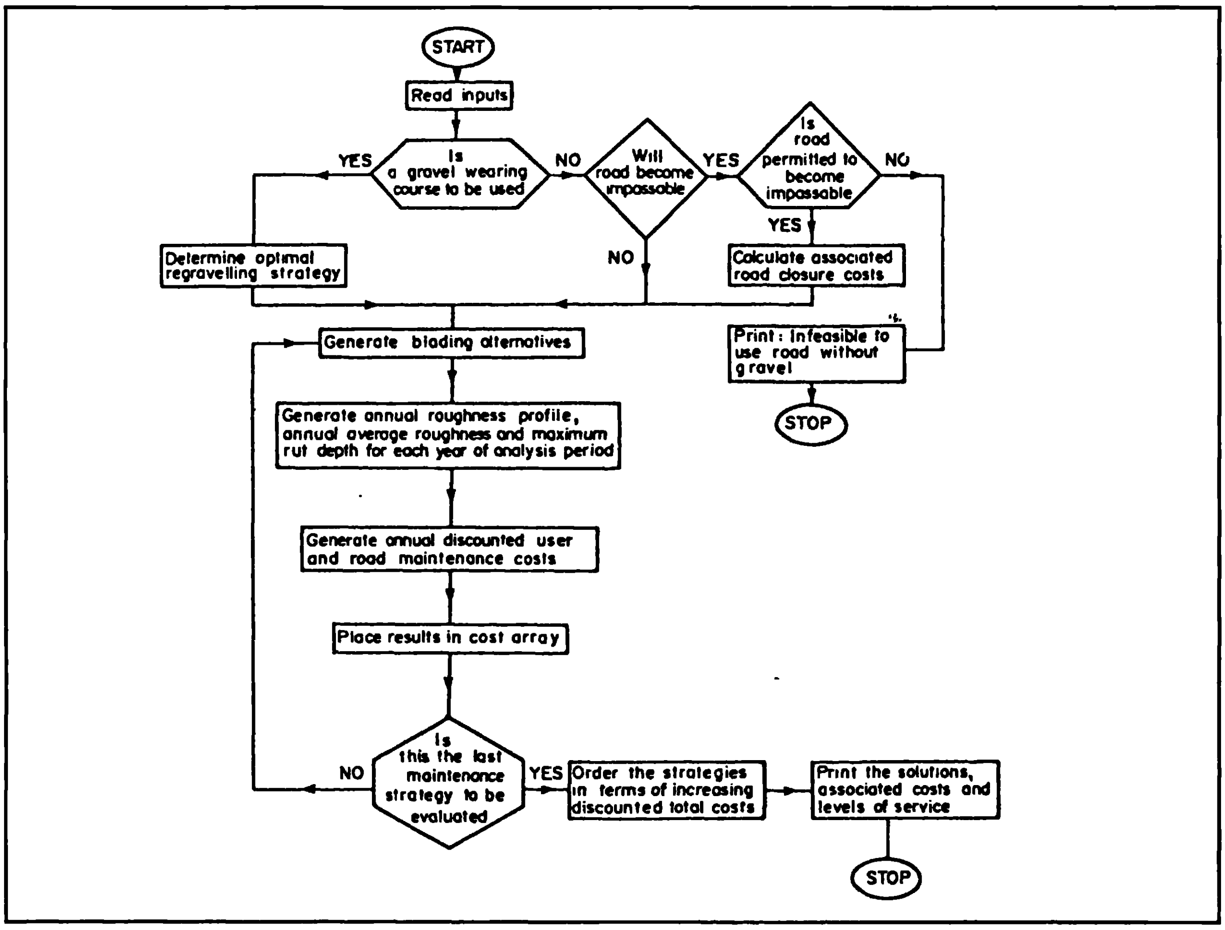

Figure 2.4 Simplified Flow Chart of the MDS (after Visser, 1981)

A number of system constraints were used in the MDS model developed by Visser, including limits on passibility and gravel wearing course minimum thickness. In the case of mine haul road MMS, limits have been established for individual defect functional performance which may be incorporated in a model, not as a design limit denoting an infeasible solution, but rather as a measure of the extent to which the optimal maintenance strategy coincides with road-user requirements established independently of cost considerations. In addition, the maintenance fleet size and productivity should also be considered as a limit when determining the optimal maintenance strategy subject to limited resources.

The analysis of costs associated with vehicle and road transport operations may be subdivided into those associated with road maintenance and those of vehicle operating costs. Winfrey (1971) presents a summary of road-user costs which is presented in Figure 2.5. Most vehicle operating costs studies have been carried out in the public domain, using paved roads and a range of public vehicles (Chesher and Harrison, 1987). No studies have been reported relating to vehicle operating costs for ultra-heavy vehicles using unpaved mine haul roads. There is thus the need to develop an analytical framework in which vehicle operating costs elements are identified and rigorously assessed as they apply to mine haul roads. Referring to the vehicle factors identified by Winfrey, the factors of fuel, tyres and maintenance can be combined to form the vehicle operating cost model. The costs of oil and lubrication typically represent less than 3% of the total vehicle operating cost (Visser, 1981 and Perkins, 1990) and as such were disregarded in the analysis. Depreciation for mine haul trucks is more a function of accounting policy, thus marginal changes in road roughness are unlikely to significantly affect truck life or depreciation policy. Of the highway and traffic factors identified by Winfrey, if construction cost is to be ignored, only road surface (in this case roughness) is considered. The remaining factors, whilst affecting road-user cost and amenable themselves to optimisation, are not directly affected by the particular maintenance strategy applied.

With regard to travel time as a cost element, the value of time is centred around the question of whether or not travel time savings are converted into extra production. Zaniewski et al (1979) in a study of vehicle travel times on low volume public roads found little effect of roughness on speed below a level of 80QI. Whilst the roughness (in terms of QI) of mine haul roads remains to be established, it is evident from theoretical vehicle simulation that reduced roughness can significantly increase production (Monroe, 1990). However, the

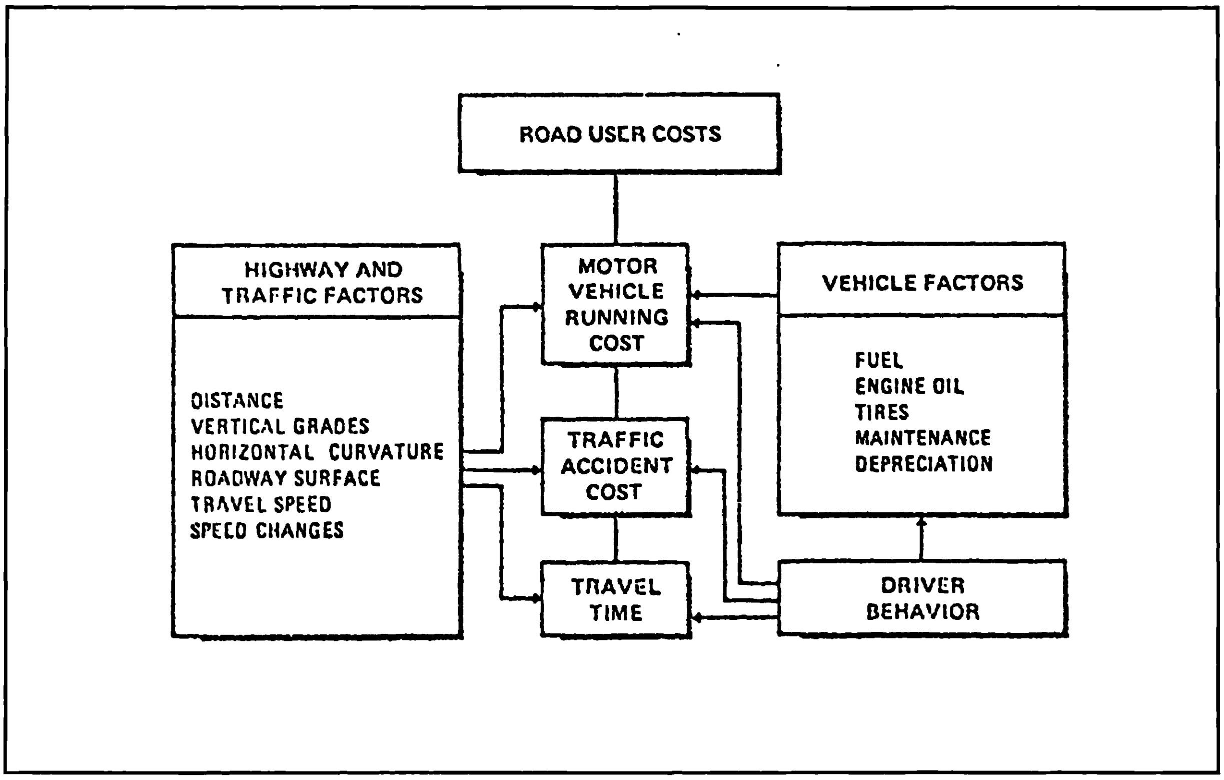

Figure 2.5 Priceable Factors of Road-user Cost Benefits (after Winfrey, 1971).

extent to which a decrease in road roughness translates practically, as opposed to theoretically, into increased production needs to be assessed and confimed from actual operating experience.

As regards vehicle accidents as a cost element, several authors have shown that these cost elements in the public domain form an inconsequential part of the total cost (Zaniewski et al, 1982 and Indiana University Institute for Research in Public Safety, 1975). Additionally, a local study into ultra-heavy hauler accidents (Stenzel, 1995) does not make adequate distinction between pavement functionality and accidents. Whilst accident costs are thus omitted from a MMS model for mine haul roads, in the event of future developments in accident data analysis and modelling this could be included in a MMS model.

The functional defects which contribute to poor functional performance have been summarised by Visser (1981) and are presented in Table 2.5 as they apply to unpaved public roads. Road roughness is seen to contribute to all the vehicle factors identified above and is the major control on total costs. Gravel loss may be omitted from the analysis since regravelling does not form part of routine maintenance activities as defined by Paterson

Table 2.5 The Impacts of Poor Functional Performance on Road User Costs (after Visser, 1981).

FUNCTIONAL DEFECT	ROAD USER COST INFLUENCE FACTORS
Roughness	Vehicle deterioration Fuel consumption Vehicle speed Accidents
Gravel loss	Influence on roughness Accidents
Rut depth	Vehicle speed Accidents
Dust	Accidents Vehicle operation:Parts and oil Vehicle speed

(1987) and as such will not impact on the optimal (short term) maintenance strategy. Rut depth may be omitted from the analysis since ruts form parallel to the direction of vehicle motion and are limited to the wheel paths most frequently trafficked and, with proper structural design, should be limited. Deslandes and Marshall (1986) comment additionally that rutting, in terms of overall road roughness, is only critical at intersections and ramps where vehicles cross ruts at acute angles. These crossings are of very limited extent in comparison to the haul length and it is thus more feasible to incorporate rutting as a contributory factor to road roughness than as a defect influencing cost factors in its own right. Although an important functional consideration, dust will not significantly affect road roughness and it is unlikely that if, when taken as a cost influence factor in its own right, any contribution to total vehicle operating costs will be discerned. The analysis of dust defect levels on vehicle operating costs faces further problems in terms of established data and models. Whilst it may be reasonable to assume that excessive dustiness will increase vehicle operating costs and accident rates on mine haul roads, no data is available to confirm this, nor the economic impact of the effect on vehicle operating costs.

2.5 Summary

Early reactionary haul road structural design techniques were superseded by the CBR design technique which has, with minor modifications, been used as the main tool for the structural design of mine haul roads. Although the CBR approach is an elementary and straight forward empirical structural design technique, based on and improved by considerable design experience, numerous disadvantages exist when applying the method to haul road structural design:

(i) The method has its base in Boussinesq's semi-infinite single layer theory which assumes a constant elastic modulus for the material. Mine haul road structures consist of numerous layers of differing materials each with its own specific elastic and other engineering properties.

(ii) More specifically, the CBR method was based on empirical results relating to the design of asphalt surfaced airfield pavements, subsequently modified for aircraft loads of up to 4 400kN. Although mine haul roads are subject to similar load levels, simple extrapolation of these empirical design criteria in conjunction with different axle geometries and gravel surfaced roads and stabilised- or rock-base layers can lead to errors of under- or over-design.

The method is thus exclusively recommended to haul road structural design cases incorporating single layers only. However, the method can, when applied judiciously, be used to determine safe (total) cover over in-situ materials, although the extent of over- or under-design remains to be quantified. Where cemented or stabilised layers are included in the design, or where the optimal structural design is sought, other design techniques should be employed which can account for the different pavement layer material properties and more accurately predict their performance under the action of ultra-heavy axle loads.

One of the tenets of the CBR cover thickness design technique is the determination of the bearing capacity of the in-situ pavement layers. This can be estimated by using the Dynamic Cone Penetrometer (DCP). However, a DCP analysis alone is insufficient to fully characterise the response of a haul road to the applied loads.

When considering the performance of multi-layer structures, the mechanistic design approach is more appropriate. Analysis of pavement response by simulation, as opposed to the empirical CBR approach, requires that the effective elastic moduli and stress sensitivity of the materials comprising the pavement structure be known, together with suitable limiting design criteria. No published data exists in regard to mechanistic limiting design criteria applicable to the design of mine haul roads. With regard to the selection of effective elastic moduli values, data pertaining to the mechanistic design of paved and unpaved roads in the public domain may provide a suitable point of departure for determining equivalent values for mine haul road construction materials.

With regard to the functional design element, the commonality between typical defects reported for unpaved public roads and the functionality requirements for mine haul roads indicates that existing specifications for unpaved public road wearing course construction materials may form a suitable base for the development of specifications for mine haul roads. Such a specification is described in TRH20 (Committee of State Road Authorities, 1990), based on sampling, testing and monitoring the performance of various test sections. It is important that any specification adopted for mine haul roads enables qualitative predictions to be made concerning likely functional performance of the road in terms of the defects such a material will exhibit when used as a wearing course. The most tractable approach is thus to assess the suitability of the TRH20 specification in relation to mine haul road wearing course material selection. From previous studies on unpaved roads, the material properties, climate, traffic and geometrics are generally considered to be the major variables affecting performance of unpaved roads. The numerous existing specifications for mine haul road wearing course selection (generally of obscure derivation or based on local experience) only refer to one or two variables and have not been assessed in terms of their reliability and acceptability in practice, no evidence exists to suggest any of them are performance related. There is thus the need to investigate the suitability of existing material selection guidelines in terms of required and actual functional performance, based on the full range of variables affecting material performance.

The maintenance of mine haul roads is an integral component of both the structural and functional designs. However, the management and scheduling of mine haul road maintenance has not been widely reported in the literature, primarily due to the subjective and localised nature of operator experience and required functionality levels. No studies have been reported relating to vehicle operating costs for ultra-heavy vehicles using unpaved mine haul roads. There is thus the need to develop an analytical framework in which vehicle operating costs elements are identified and rigorously assessed as they apply to mine haul roads. Existing MMS are based on the optimisation of pavement functional performance and vehicle operating and road maintenance costs and a similar approach is proposed for the development of mine haul road MMS.

CHAPTER 3

EXPERIMENTAL DESIGN AND DATA COLLATION

3.1 Introduction

This chapter addresses the experimental designs adopted as a basis for the derivation of the structural and functional designs for mine haul roads. The experimental designs adopted to address each intermediate component research activity are described and outlined in terms of the measurement of site variables. The various mine test sites available and the extent to which each site fulfils the data requirements envisaged in the experimental designs are then reviewed. For the maintenance management system design, a maintenance management model is described from which the vehicle operating and road maintenance data collation requirements are identified and summarised.

3.2 Experimental Design for Structural Design Research

The following set of independent variables (factors) are recognised as those predominantly controlling the structural performance of a haul road:

(i) Applied load/stress
(ii) Subgrade strength
(iii) Structural thickness and layer strengths

The approach advocated involves the quantification of the factors given above for existing haul roads to determine the efficacy of the various design options. To fully characterise the structural performance of existing or future designs of haul roads, each factor should be analysed at various levels. A designed factorial experiment is the most efficient in analysing a combination of factors. The factors listed above, together with their levels of analysis are incorporated in the sample matrix for the structural design research given in Table 3.1. For each of the above independent variables actual field values will be recorded. In addition, the following dependent variables are also be measured, namely:

(i) Resilient deformations in each of the layers and in the subgrade.

(ii) Permanent deformation after a number of load repetitions.

Table 3.1 Sample Matrix for Structural Design Research.

SUBGRADE STRENGTH		WEAK			STRONG		
WHEEL LOAD (Low, Medium, High)		L	M	H	L	M	H
STRUCTURAL THICKNESS	Thin						
	Medium						
	Thick						

From these results, the stresses and strains in each pavement layer can be back calculated. This will then provide a solution to the critical stresses and strains developed in the pavement under the action of ultra-heavy wheel loads and the combination of pavement layers that would be required to ensure adequate structural performance.

To quantify the variability of the results under identical conditions, at least three site replications will be required. If all the factors and levels can be accommodated, 27 separate sets of measurements are required. However, the wheel loads can be varied on each site and therefore only 9 sites are required.

3.2.1 Measurement of Site Variables

The measurement and collation of site variable data is summarised in Table 3.2. and discussed in the following sub-sections.

A test section or sections that exhibit factor level combinations stipulated in Table 3.1 was located on a mine's haul road. An indication of the bearing capacity of the subgrade in that location was obtained with the dynamic cone penetrometer (DCP) down to a depth of 1800mm at the point where the multi-depth deflectometer (MDD) is to be installed. Structural thickness data was obtained from historical road design data, corroborated with

Table 3.2 Summary of Dependant and Independent Variable Measurement Systems.

VARIABLE	MEASUREMENT SYSTEM
Applied load	Measured gross vehicle weight, axle load and tyre pressure.
Subgrade conditions	Dynamic Cone Penetrometer and/or piezometer probe testing.
Resilient strains and permanent deformations	Multi-depth deflectometer (MDD) installations.

DCP data for individual pavement layer thickness assessment and depth of transducer installation.

3.2.1.1 Applied Load

Load application was achieved through the use of a selection of light, medium and heavy trucks. Actual wheel loads were determined by measurement where on-board monitoring was available. In other cases, recourse was made to tyre test statistical data to determine average laden and unladen vehicle masses. In all cases, vehicle manufacturers data was used to determine axle loadings and tyre pressures.

3.2.1.2 Dynamic Cone Penetrometer

The DCP instrument is shown schematically in Figure 3.1. It comprises a 16mm diameter rod which is driven into the pavement using a built-in 8kg hammer falling a standard distance of 575mm. The instrument measures the penetration per blow into a pavement through each of the pavement layers, upto a depth of 800mm. Since haul road structural thicknesses are in excess of this value, an extension rod is used which enables shear strength profiles to be taken upto a depth of 1800mm. The penetration rate in terms of mm/blow, called the DCP Number (DN), gives an indication of the in-situ shear strength of a material. The DCP is highly correlated to the CBR as discussed by Kleyn (1975) and Kleyn et al (1982).

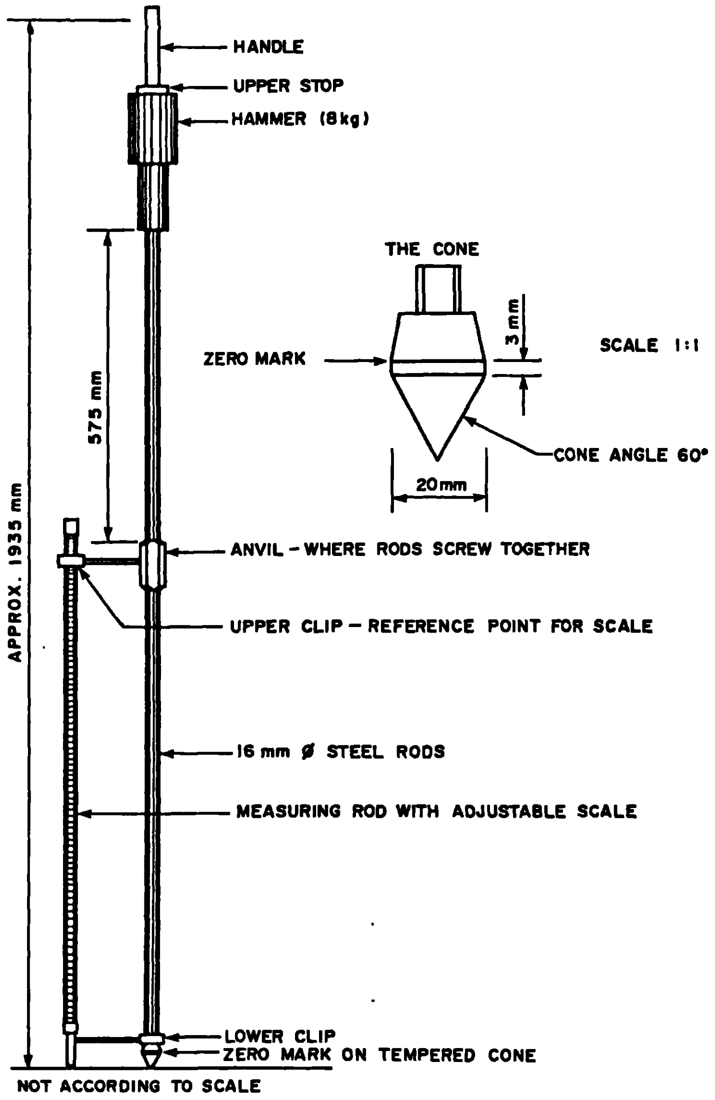

Figure 3.1 The Dynamic Cone Penetrometer (after CICTRAN, 1992).

Although the DCP has been used extensively, little work has been done to correlate DCP derived CBR's with the effective elastic moduli of pavement layers. A tentative correlation has been suggested by De Beer et al (1989) based on a dual 20kN wheel load. The effective modulus thus determined could prove to be a suitable seed value for the back-calculation of effective layer moduli from deflection measurements, assuming the correlation holds true for wheel loads considerably exceeding this value.

3.2.1.3 Multi-depth deflectometer

Analysis of pavement response by simulation techniques requires that the elastic moduli and stress sensitivity of the various materials comprising the pavement layers be known. The technique of measuring permanent and resilient deformations using the Multi-Depth Deflectometer (MDD) system is well established and provides a reliable method of back-calculating layer response parameters (De Beer et al, 1989, Basson et al, 1981). These parameters form the basis of any analytical model used to model pavement structural performance.

The MDD system is described by De Beer et al (1989). It comprises a number of linear voltage differential transducers (LVDT's) installed vertically at various depths coincident with interfaces of the structural layers. The LVDT, together with its clamping unit is illustrated in Figure 3.2.

Each MDD module comprises one LVDT and a housing unit incorporating a clamping nut, spring, cable ducting, loading washer, ball bearings and rubber membrane. The module is inserted in a neoprene membrane lined hole and clamped in position by means of the clamping nut. Several MDD modules may be inserted in one hole, as shown in Figure 3.3.

The interconnecting rod running the length of the hole, through each MDD, is anchored at a reference depth where deflection is assumed to be zero, the assumption being validated during the measurement program. To accomodate the multi-layer structures encouintered on mine haul roads, 6 MDD modules were incorporated in each installation. On the surface of the road the installation is capped and the module cables ducted to the computerised data acquisition system. A load is applied by the wheels of a haul truck and the associated resilient and permanent deformations recorded, together with the location of the load in respect to the position of the MDD array. Evaluations of the repeatability of the results generated from similar exercises revealed relatively low coefficients of variation in the MDD deflection results (Basson et al, 1981). At least four repeats of the same measurement are needed to obtain an accuracy of 95% for a confidence limit of 99%.

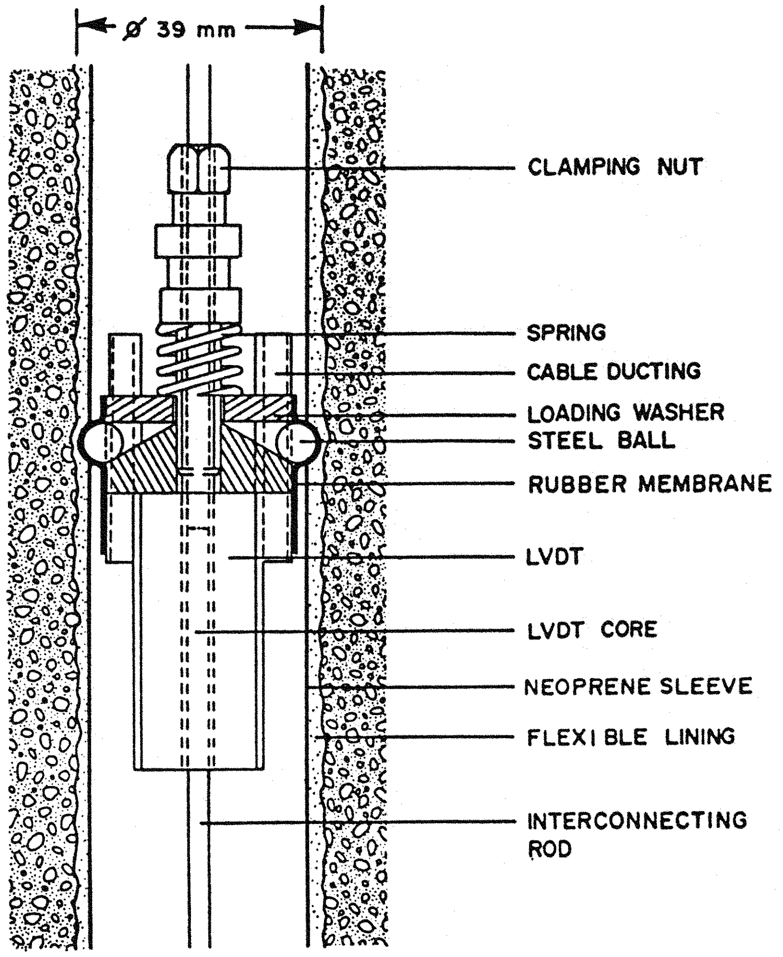

Figure 3.2 Components of a Multi-depth deflectometer (MDD) module (after De Beer et al, 1989)

3.2.2 Mine Test Site Factor Summary

The multi-level designed factorial experiment referred to in section 3.2 forms the basis for the location of suitable test sites. For each test site the range of independent variables are assessed and summarised in the following sub-sections.

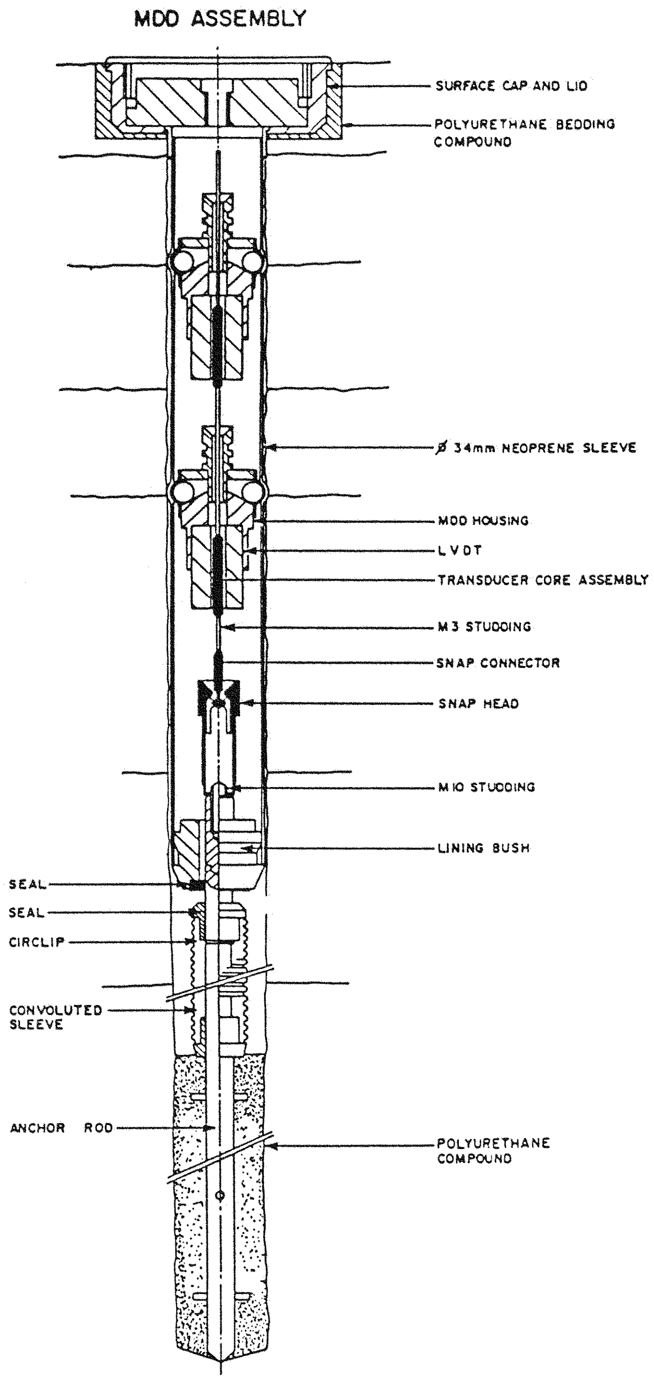

Figure 3.3 Multi-depth deflectometer in the pavement structure (after De Beer et al, 1989)

3.2.2.1 Kriel Colliery

Applied loads

The following vehicles were available for the application of loads, either full or empty;

(i) Euclid R170 rear dump truck
(ii) Caterpillar 772B bottom dump truck
(iii) Euclid R50 rear dump truck
(iv) Euclid R85 water tanker

Table 3.3 summarises the tyre load data for each truck type.

Structural Thickness and Strength

Structural thickness varied from 950mm to 5000mm on either rock base, saturated in-situ material or sandstone fill material. Three distinct structures were seen as a result of various construction techniques used;

(i) A low strength sub-grade construction in the vicinity of CH500-700 on main haul road, including medium strength ferricrete base and sub-base layers (non-stabilised).
(ii) A low strength sub-grade on Pit 23 haul road, CH700, including a base layer of ex-pit shale and sandstone on low strength ferricrete sub-base.
(iii) A medium strength sub-grade on the main haul road, CH280, including a stabilised base above a medium strength ferricrete sub-base.

The Pit 23 haul road is approximately 6 years old and has been heavily trafficked, as has the main road which is approximately 13 years old. The haul road extension in the vicinity of the pan is new and as such lightly trafficked. It is however showing signs of distress due to water seepage into the road from the pan area and weak in-situ material. The rock base has been incorporated in the road as a remedial measure.

From this data, three test sites were located to complete critical factor level combinations envisaged in the experimental design (section 3.2). These sites are summarised below and

Table 3.3 Vehicle Specifications and Applied Loads - Kriel Colliery.

VEHICLE TYPE	**Euclid R170 (Special body)**			**Caterpillar 772B**				**Euclid R50**			**Euclid R85 water truck**		
	Total	**Front**	**Rear dual**	**Total**	**Front**	**Drive dual**	**Rear dual**	**Total**	**Front**	**Rear dual**	**Total**	**Front**	**Rear dual**
Vehicle mass (tons)													
Full	320			170				80			118		
Empty	130			70				35			51		
Load distribution (%)													
Full		45	55		14	38	48		35	66		36	64
Empty		40	60		25	40	35		49	51		46	54
Tyre load (kN)													
Full		406	429		113	161	201		137	130		208	185
Empty		255	191		85	68	60		84	44		112	66
Tyre Pressure (kPa)		630	630		630	630	630		630	630		630	630

their locations given in Figure 3.4.

SITE 1	CH563.00 Stream diversion area of pit 23 road, thin structure on weak sub-grade material.
SITE 2	CH700.00 Pan area of pit 23 road towards ramp 10, thick structure on weak sub-grade material.
SITE 3	CH280.00 Alongside old ramp 4 on original haul road, thick structure on strong sub-grade material.

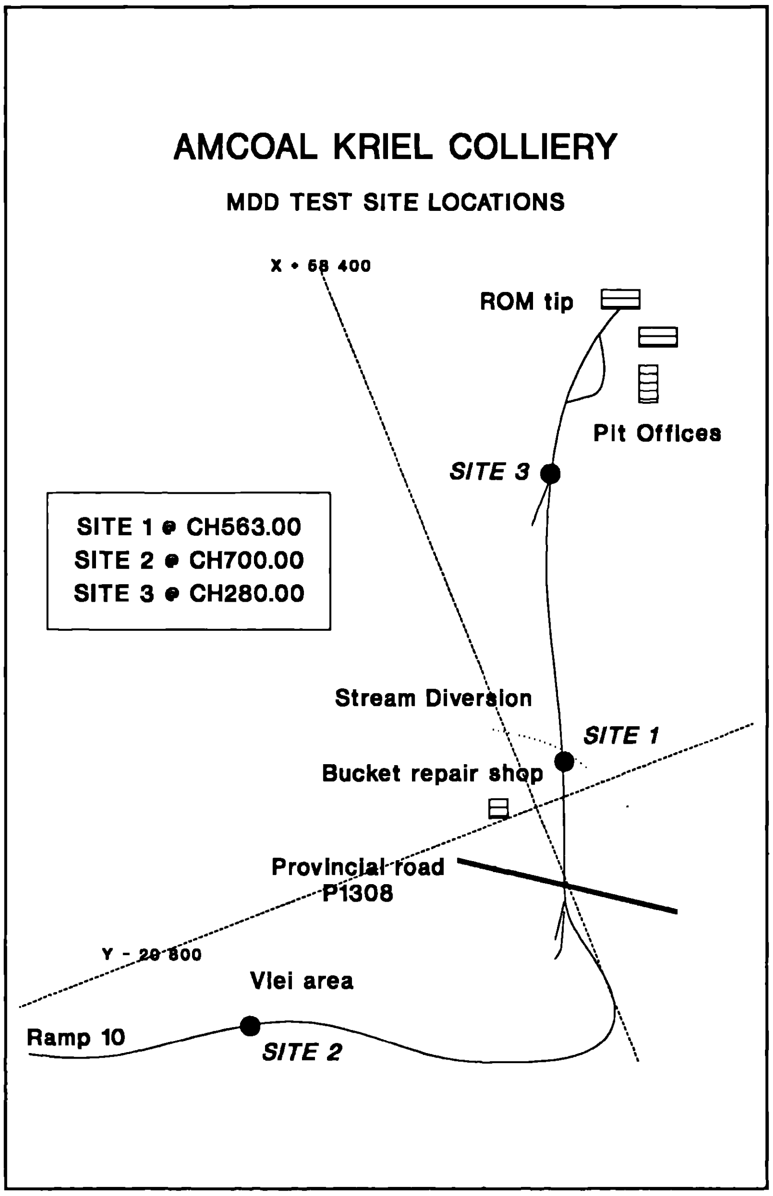

Figure 3.4 Test site locations for structural analysis - Kriel Colliery.

3.2.2.2 Kromdraai Colliery

Applied loads

The following vehicles were available for the application of loads, either full or empty;

(i) Komatsu HD785-3 rear dump truck
(ii) Dresser haulpak 630E rear dump truck with on-board load monitoring

Table 3.4 summarises the tyre load data for each truck type. Typical laden weights are given for the 630E whilst actual loadings were used in the pavement response models.

Table 3.4 Vehicle Specifications and Typical Applied Loads - Kromdraai Colliery.

VEHICLE TYPE	**Dresser haulpak 630E**			**Komatsu HD785-3**		
	Total	**Front**	**Rear dual**	**Total**	**Front**	**Rear dual**
Vehicle mass (tons)						
Full	285			138		
Empty	113			60		
Load distribution (%)						
Full		33	67		32	68
Empty		48	52		47	53
Tyre load (kN)						
Full		419	431		216	230
Empty		272	142		138	78
Tyre Pressure (kPa)		630	630		630	630

Structural Thickness and Strength

Structural thickness varied from 1200mm to 4000mm on in-situ material or sandstone fill material. Two distinct road structural designs were discerned, that constructed by a contractor and by the mine. The latter construction comprised only a thin layer of wearing course material.

All possible locations exhibited a strong sub-grade strength. Construction materials used in the base and sub-base consisted of compacted ferricrete lain upon fill or in-situ ferricrete. The main haul road is approximately 18 months old and has been lightly trafficked.

From this data, three test sites were located to complete critical factor level combinations envisaged in the experimental design (section 3.2). These sites are summarised below and their locations given in Figure 3.5.

SITE 1	CH2800.00 Contractor constructed section, thin structure, strong sub-grade material.
SITE 2	CH1900.00 Mine constructed section, medium structural thickness, strong sub-grade material.
SITE 3	CH1075.00 Mine constructed section in deep fill area, thick structure, strong sub-grade material.

3.2.2.3 New Vaal Colliery

Applied loads

The following vehicles were available for the application of loads, either full or empty;

(i) Euclid R170 rear dump truck
(ii) Komatsu HD785-3 rear dump truck
(iii) Komatsu HD1600M-1 rear dump truck
(iv) Komatsu HD460 water truck

Table 3.5 summarises the tyre load data for each truck type.

Structural Thickness and Strength

Structural thickness varied from 650mm to 3200mm on in-situ material. Three distinct road structural designs were discerned, that of the original design (contractor construction), and mine construction incorporating progressively thinner structures as road building proceeded northwards.

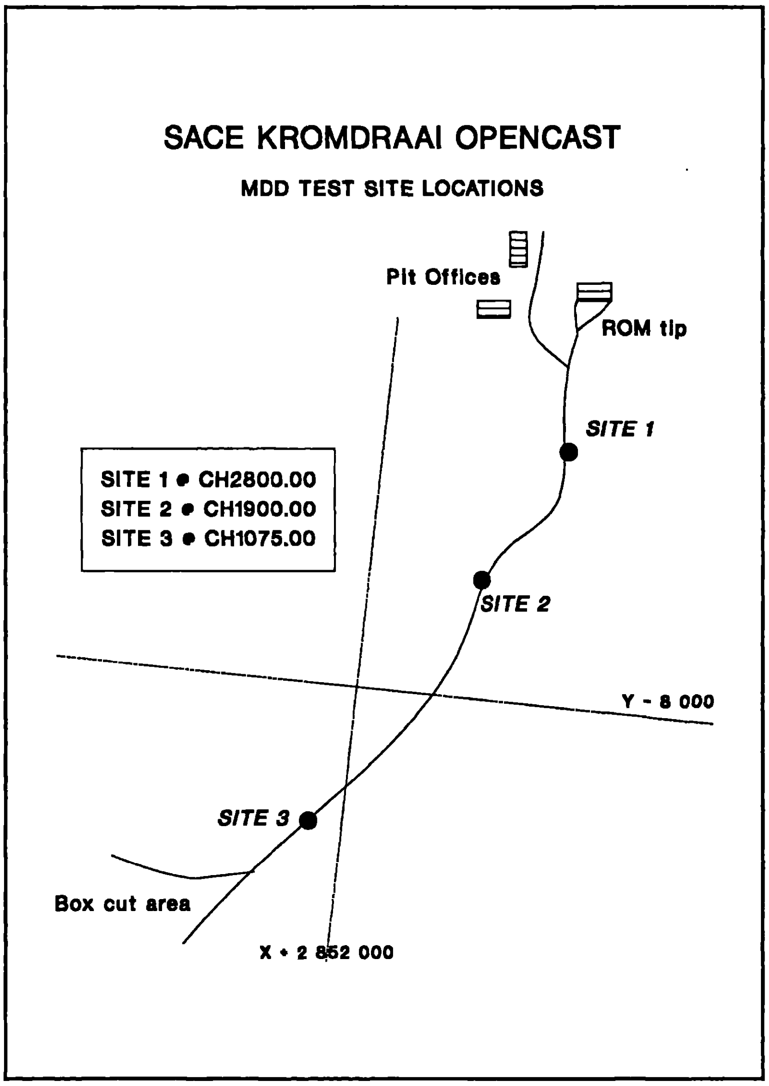

Figure 3.5 Test site locations for structural analysis - Kromdraai Colliery.

(i) Original specification road has a structural thickness of 1300mm, cut and filled sub-grade depth of 1000mm.

(ii) Vlei (or marsh) area construction called for ±6000mm fill which was subsequently reduced by the mine to 2000mm below a 1200mm structure.

(iii) Extension to Apple cut consists of 1500mm fill under a structural thickness of 650mm.

All possible locations are underlain by the Vaal River sands, extending to a depth of 8-12m. Previous testwork (Hawkins, Hawkins and Osborne, 1982) reports CBR values generally low, from CBR 5-10 in the vlei area to CBR 15-19 in other areas. Construction materials

Table 3.5 Vehicle Specifications and Applied Loads - New Vaal Colliery.

VEHICLE TYPE	Euclid R170			Komatsu HD785-3			Komatsu 1600M-1			Komatsu HD460 water truck		
	Total	**Front**	**Rear dual**	**Total**	**Front**	**Rear dual**	**Total**	**Front**	**Rear dual**	**Total**	**Front**	**Rear dual**
Vehicle mass (tons)												
Full	257			138			267			85		
Empty	102			55			107			37		
Load distribution (%)												
Full		32	68		31	69		33	67		32	68
Empty		50	50		47	53		49	51		50	50
Tyre load (kN)												
Full		402	429		210	216		401	439		131	144
Empty		250	127		127	78		257	134		92	46
Tyre Pressure (kPa)		630	630		630	630		630	630		630	630

used in the base and sub-base consist of compacted clinker, coal discards (shale and sandstone) and soft plinthite (ratio 1:1:1).

The main haul road is approximately 10 years old and has been heavily trafficked. Some evidence of structural failure is seen in the vlei area of the road where sand is pushing through the pavement layers.

From this data, three test sites were located to complete critical factor level combinations envisaged in the experimental design (section 3.2). These sites are summarised below and their locations given in Figure 3.6.

SITE 1	CH1200.00 Contractor constructed section, deep fill, thick structure, strong sub-grade material.
SITE 2	CH3300.00 Mine constructed section, medium structure, weak sub-grade material.
SITE 3	CH4800.00 Mine constructed section, medium thick structure, weak sub-grade material.

Table 3.6 summarises the factor coverage envisaged in the factorial design (section 2.3), the factor levels available at each mine site being given. From this table it is seen that the full range of structural design options envisaged from various factor/level combinations were quantified and analysed.

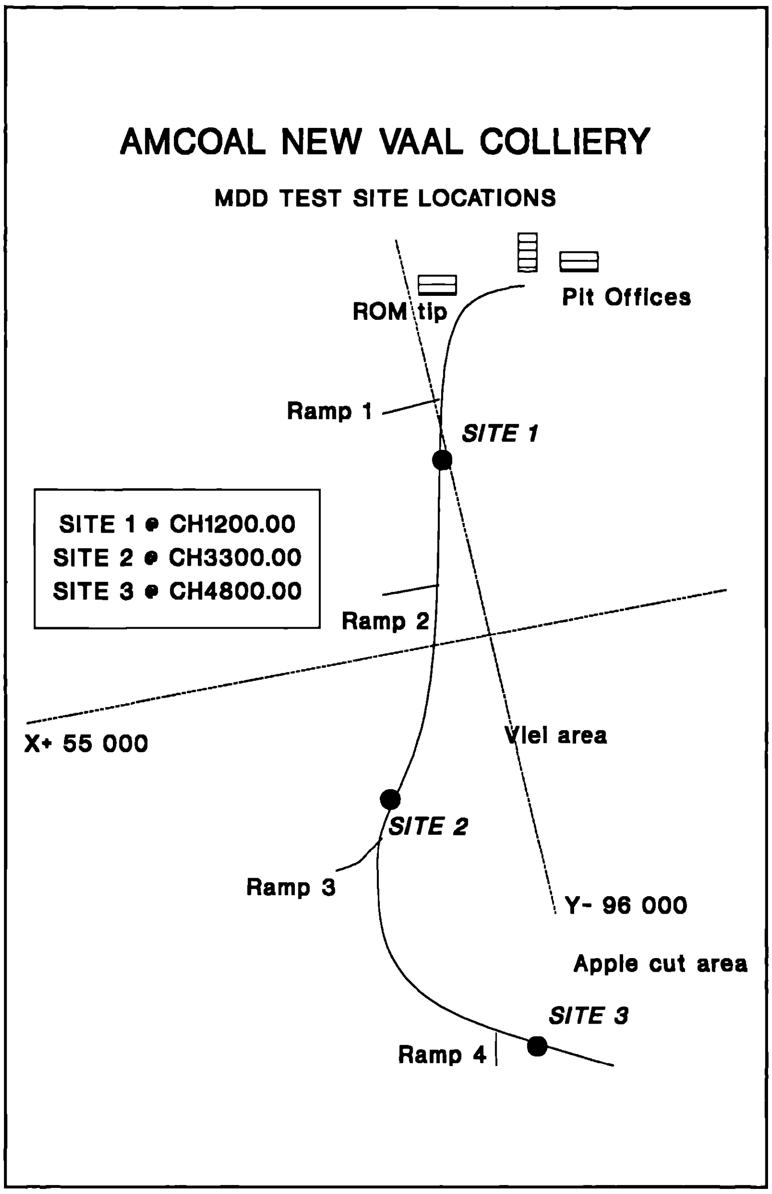

Figure 3.6 Test site locations for structural analysis - New Vaal Colliery.

Table 3.6 Test Site Location Matrix for Structural Design Research.

SUBGRADE STRENGTH		**WEAK**			**STRONG**		
WHEEL LOAD (Low, Medium, High)		**L**	**M**	**H**	**L**	**M**	**H**
STRUCTURAL THICKNESS	**Thin**	Kriel site 1	Kriel site 1	Kriel site 1	Kromdraai site 1	Kromdraai site 1	Kromdraai site 1
	Medium	New Vaal site 2	New Vaal site 2	New Vaal site 2	Kromdraai site 2	Kromdraai site 2	Kromdraai site 2
	Thick	Kriel site 2 New Vaal site 3	Kriel site 2 New Vaal site 3	Kriel site 2 New Vaal site 3	Kriel site 3 New Vaal site 1	Kriel site 3 New Vaal site 1 Kromdraai site 3	Kriel site 3 New Vaal site 1 Kromdraai site 3

3.3 Experimental Design for Functional Design Research

The primary objective of this part of the study was to survey the functional performance of existing wearing course materials used for haul road construction and to ascertain the validity and applicability of published selection guidelines. The most efficient approach entails the analysis of a number of in-service mine roads which cover a full range of the major factors influencing functional performance. This is best achieved through use of a designed factorial experiment where the relevant independent variables (factors) are analysed at various levels.

From previous studies on unpaved public roads (Visser, 1981, Paige-Green, 1989), the wearing course material, road geometrics, climate and traffic are considered to be the major independent variables (factors) affecting the performance of unpaved roads. When applied to mine haul road functional analysis, traffic may be disregarded as an independent variable, although, under certain circumstances it is possible to assess similar materials at one mine under different traffic volumes. Recording the functional performance of the road was limited to the laden side of the road whilst any exceptions seen on the unladen side were additionally recorded.

The choice of wearing course materials as a factor is problematic in terms of its sub-division into a number of divisions of one or other property, the extensive testing required being impractical. A more rational approach has been outlined by Weinert (1980) in which rock types are grouped by their weathering products and geotechnical behaviour, irrespective of their genesis. The following nine material groups are used;

(i) Basic crystalline rocks, eg. basalt, amphibolite, dolerite
(ii) Acid crystalline rocks, eg. felsite, gneiss, granite
(iii) High silica rocks, eg. chert, quartzite, hornfels
(iv) Arenaceous rocks, eg. Arkose, sandstone, mica-schist
(v) Argillaceous rocks, eg. shale, mudstone, phyllite
(vi) Carbonate rocks, eg. dolomite, limestone , marble
(vii) Diamictites, eg. tillite
(viii) Metalliferous rocks, eg. magnesite, magnetite, ironstone

(ix) Pedocretes, eg, calcrete, ferricrete, laterite

Several of these groups may be disregarded for the purposes of haul road wearing course material selection, due in most part to their limited occurrence in the vicinity of most Transvaal strip coal mines. In addition, although not a weathering product, mixtures of materials must also be considered as a factor level. Factor levels thus considered for the factor of material type are then pedocretes, argillaceous, arenaceous, basic crystalline and acid crystalline, together with mixtures of these.

The choice of levels for the independent variable of climate was based on Weinert's N-value (Weinert, 1980). Weinert's N-value describes the durability of road-building material, based on the relationship between calculated evaporation rates (for the warmest months of the year) and the averaged monthly rainfall. This choice is advantageous since the weathering products used as levels for the independent variable of wearing course material are unique for the particular N-value contour chosen, although as will be shown later, this and the physical location of the mines limits the range of materials available for analysis. In addition, the N-values of 2, 5 and 10 are distinct physiographical boundaries and most Transvaal strip coal mines are situated within the physiographical region where N=2 to N=5 as shown in Figure 3.7. This effectively discounts climate as an independent variable in the analysis.

Road geometrics are considered in terms of a section of homogenous, straight road, either level or grade, 200m long. It was not always possible to satisfy these demands entirely, especially for level sections, but significant deviations from the factor level are noted where applicable. The factors and levels of analysis discussed above are incorporated in a sample matrix as given in Table 3.7 and the following additional dependent variables were also recorded for each test section envisaged in the sample matrix;

- Days since last maintenance
- Traffic (t/day)
- Moisture conditions of surface layer
- Surface erosion
- Surface drainage

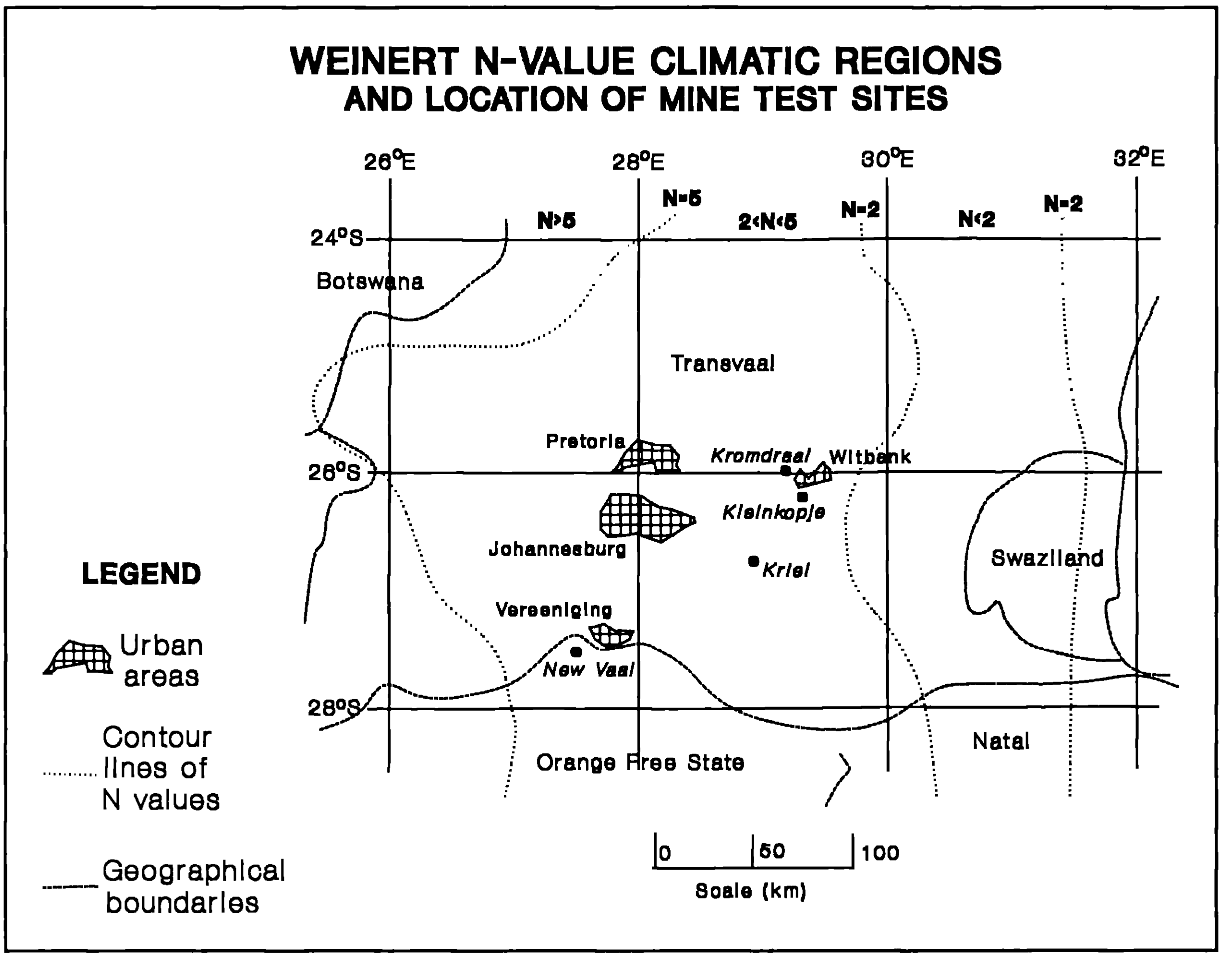

Figure 3.7 Location of Mine Test Sites in Relation to Weinert's N-values.

Table 3.7 Sample Matrix for Functional Design Research

Wearing Course Material (weathering group)	**Road Geometrics**	
	Level	Grade
Pedocretes		
Argillaceous		
Arenaceous		
Basic crystalline		
Acid crystalline		
Mixtures		

Table 3.8 Summary of Dependent and Independent Variable Measuring Systems

VARIABLE	MEASUREMENT SYSTEM
Traffic volume	Production statistics
Wearing course material	Laboratory classification
Days since last maintenance	Mine records
Moisture conditions of surface layer	Functional assessment following 5 point scale
Surface drainage conditions	Functional assessment following 5 point scale
Surface erosion	Functional assessment following 5 point scale
Functional performance	Functional assessment following 5 point scale of degree and extent
Road geometry	Survey plans
Rut depth and corrugation geometry	Straight edge

3.3.1.2 Functional Performance Evaluation

A visual evaluation was used for the qualitative determination of surface moisture conditions, roadside and on-road drainage and erosion (longitudinal and cross directions). The variables affecting haul road functional performance were derived from consideration of the properties of the wearing course surface (material type), those related to the road formation and those related to the way the road user experiences the road. The following defects were considered, both in terms of degree (how adverse is the defect) and extent (how much of the road is affected), except for formation and functional defects, which are only considered in terms of extent.

- Wearing course
    - Potholes
    - Corrugations
    - Loose material
    - Dustiness
    - Stoniness - fixed
    - Stoniness - loose
    - Cracks - longitudinal

  - Cracks - slip
  - Cracks - crocodile

- Formation
  - Drainage - on the road (crossfall)
  - Drainage - side of road (longitudinal)

- Function
  - Skid resistance - wet
  - Skid resistance - dry
  - Erosion - longitudinal direction
  - Erosion - cross direction

A general description of degrees and extents, as proposed for the evaluation of mine haul roads together with the evaluation criteria for each defect analysed, are covered in more detail in Chapter 9.

These defects were used to determine the functionality of a particular road, in terms of a total defect score, derived from consideration of the sum of each defect degree and extent product in the analysis. Monthly recordings were made at each mine test site to generate a profile of the variation of defect score with the other dependent variables analysed. No riding quality readings were taken using linear displacement integrators since no useful comparative values exist and additionally, no relationship exists between riding quality as measured by a small car and the equivalent quality as experienced by a large haul truck. The more tractable approach is to determine overall riding quality in terms of a defect index and, in conjunction with performance acceptability criteria, deduce the extent to which each material type meets the required criteria.

3.3.1.3 Rut Depth and Corrugation Geometry

A 2m straight edge and tape were used to measure rut depth and corrugation geometry.

Actual rut depth and corrugation wavelength and amplitude measurements were used to determine the degree of the defect as opposed to any trend in the measurements with time. Isolated values were recorded to correlate defect degree with approximate rut depth. A visual assessment was made of the extent of the defect over the road.

3.3.2 Mine Test Site Factor Summary

The multi-level designed factorial experiment described in section 3.3 forms the basis for the location of suitable test sites. For each mine test site identified, the range of independent variables are assessed and summarised in the following sub-sections.

3.3.2.1 Kriel Colliery

Traffic Volume

Kriel Colliery produced between 250-350kt run-of-mine (ROM) product per month over the analysis period. This may be equated to between 1 793 and 2 427 truck repetitions (all trucks being converted to R170 equivalents) using an average load factor of between 141t and 159t per truck. The mine fleet consists of five Euclid R170 (single rear axle with dual wheels) trucks, one Caterpillar 772B (horse single rear dual wheel axle and trailer single dual wheel axle) bottom dump truck and two Electra-haul BD180 (horse single rear dual wheel axle and trailer single dual wheel axle) bottom dump trucks. Mine production tonnage (ie. traffic volume) data is not specific to individual truck types and it is therefore difficult to isolate the functional effect of one particular truck type from another. Assuming similar operating conditions for all truck types, 68% of the total tonnage hauled can be ascribed to the R170 truck. Use of an equivalent vehicle converts the mine fleet to the R170 truck type which, in terms of wheel loadings and axle configuration, is likely to give the upper limit to the road deterioration modes and rates with traffic. It is therefore assumed that there is negligible difference between the effect of the mine fleet (as operated) and the assumed equivalent fleet of R170 trucks in terms of the effects on haul road functionality.

Although coal is sourced from four areas, only two traffic volumes can be assessed at various points along the road and the unladen traffic volume repetitions are similar.

Wearing Course Material

Two distinct wearing course materials were discerned at Kriel;

(i) Ferricrete, ash and decomposed dolerite (various proportions not strictly controlled but approximate values are 70%, 20% and 10% respectively).

(ii) Ferricrete from local borrow pits

Table 3.9 gives the results of the laboratory analysis of the wearing course material at Kriel Colliery test sites. The ferricrete, ash and decomposed dolerite mixtures were similar in terms of grading, the top size being less than 19,00mm although site 1 material was classified as a fine gravel whilst site material 2 was classified as a sand by virtue of the greater proportion of fine material present. Site 3, being composed exclusively of ferricrete, exhibits a top size of less than 13,20mm and a greater proportion of course and medium fine sand than sites 1 and 2. Grading modulus values were similar for all three sites and the plasticity indices appear to be related to the material mixture used; sites 1 and 2 exhibiting higher plastic limit (PL), liquid limit (LL) and linear shrinkage values than the pure ferricrete of site 3. The bearing strength of the materials (in terms of California Bearing Ratio, 7 day soaked CBR) revealed that the pure ferricrete of site 3 had better bearing strength below 95%Mod. AASHTO compaction than the mixtures at sites 1 and 2. The bearing strength of the site 1 mixture was far in excess of that at site 2, the latter exhibiting little increase in strength above 97%Mod.AASHTO.

When the laboratory analysis of the material is considered in terms of the TRH14 (CSRA TRH14, 1985) requirements, each site is classified as comprising a G6 type of material although site 3 (ferricrete) approaches close to a G5 grading.

Road Geometrics

Approximately level road sections were located on road sections exhibiting both wearing course material types. Grade sections limited in length to about 120m at a grade of 3,25% were only available on a section comprising ferricrete, ash and dolerite wearing course.

Table 3.9 Laboratory Analysis of Wearing Course Material at Kriel Mine

SAMPLE SITE: KRIEL COLLIERY	**Site 1**	**Site 2**	**Site 3**
SAMPLE DESCRIPTION	Dark grey weathered dolerite, pale red ferricrete and bottom ash. Fine gravel.	Dark grey weathered dolerite, pale red ferricrete and bottom ash. Sand.	Dark brown ferricrete. Sand.
SCREEN ANALYSIS (%) PASSING			
75.00mm	100	100	100
63.00	100	100	100
53.00	100	100	100
37.50	100	100	100
26.50	100	100	100
19.00	100	100	100
13.20	99	97	100
4.75	93	91	92
2.00	67	66	73
0.425	37	40	51
0.075	19	22	21
SOIL MORTAR			
Coarse sand 2.00-0.425mm	46	38	28
Coarse fine sand 0.425-0.250mm	8	9	13
Medium fine sand 0.250-0.150mm	8	8	13
Fine sand 0.150-0.075mm	10	12	15
Material <0.075mm	28	33	29
CONSTANTS			
Grading modulus	1,23	1,28	1,45
Liquid limit	21	24	18
Plasticity index	6	8	4
Linear shrinkage (%)	3	4	2
Sand equivalent			
Classification - TRB	A-1-b(0)	A-2-4(0)	A-2-4(0)
Classification - TRH14	G6	G6	G6
MOD. AASHTO			
Max dry density (kg/m^3)	2359	2307	2227
OMC (%)	5,4	7,6	7,4
MMC (%)	5,2	7,4	7,4
Dry density (kg/m^3)	2343	2309	2237
% Max dry density	99	100	100
100% Mod CBR	132	48	98
% Swell	0,1	0	0
NRB			
Dry density (kg/m^3)	2232	2217	2160
% Max dry density	95	96	97
100% NRB CBR	36	41	52
% Swell	0,1	0,1	0,1
PROCTOR			
Dry density (kg/m^3)	2154	2143	1975
% Max dry density	91	93	89
100% Proctor CBR	23	29	24
% Swell	0,1	0,1	0,1
CBR VALUES			
100% Mod AASHTO	159	48	90
98%Mod AASHTO	92	44	63
97%Mod AASHTO	70	42	52
95%Mod AASHTO	40	36	43
93%Mod AASHTO	29	29	36
90%Mod AASHTO	19	21	27

From this data, three test sites were located to complete critical factor level combinations envisaged in the experimental design (section 3.3). These sites are summarised below and their locations given in Figure 3.8.

SITE 1	CH413.00-650.00 (level), CH650.00-800.00 (grade). Stream diversion area of pit 23 road, ferricrete, decomposed dolerite and ash wearing course.
SITE 2	CH600.00-800.00 (level, no grade). Pan area of pit 23 road towards ramp 10, ferricrete, decomposed dolerite and ash wearing course.
SITE 3	CH160.00-360.00 (level), CH50.00-250.00 (grade). Alongside old ramp 4 on original haul road, ferricrete wearing course.

3.3.2.2 Kromdraai Colliery

Traffic Volume

Kromdraai Colliery produced between 248 and 366kt of ROM product per month over the analysis period. This may be equated to between 1 675 and 2 472 truck repetitions per month. Coal is sourced from a single pit and hauled on two roads. The newer road (haul road 2) was steadily exposed to increasing traffic volumes over the analysis period (May 1994 - April 1995). As from October 1994 haul roads 1 and 2 carried approximately equal traffic volumes. The coal hauling fleet consists of five Dresser-haulpak 630E (single rear axle with dual wheels) trucks, each with a GVM of 261t and an unladen GVM of 113t. These trucks may be considered approximately equivalent to the Euclid R170 trucks in terms of GVM.

Wearing Course Material

All roads were constructed using local mine ferricrete for the wearing course. Table 3.10 gives the results of the laboratory analysis of the wearing course material at Kromdraai Mine test sites. As can be seen, the grading of the material similar at sites 1 and 2 whilst site 3 material is slightly coarser, containing a smaller proportion of material less than 0,075mm. This is in the most part attributable to lower traffic volume handled by the road at the time

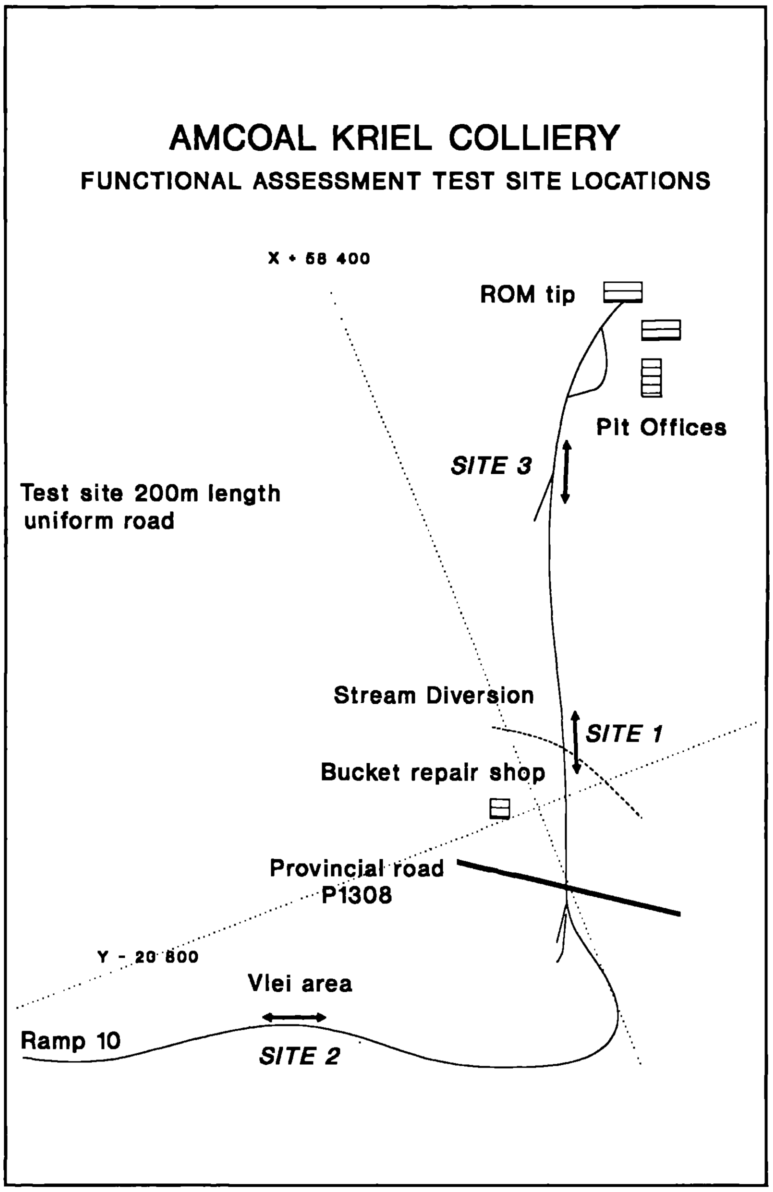

Figure 3.8 Test site locations for functional analysis - Kriel Colliery

of sampling the wearing course material. Plasticity index (PI) values for site 1 and 2 are similar at 10 and 8 respectively whilst site 3 shows a lower value of 4 attributable to a lower liquid limit and higher plastic limit. Linear shrinkage varies accordingly, the materials exhibiting high PI values also exhibiting larger shrinkage values.

Bearing strength of the materials (in terms of California Bearing Ratio, using 7 day soaked CBR) are similar for sites 1 and 2 whilst site 3 exhibits greater bearing strengths over the range of compaction. Accordingly, Sites 1 and 2 are accorded a classification following

Table 3.10 Laboratory Analysis of Wearing Course Material at Kromdraai Colliery

SAMPLE SITE: KROMDRAAI COLLIERY	Site 1	Site 2	Site 3
SAMPLE DESCRIPTION	Dark red quartz. Sandy gravel.	Light red quartz. Sand	Light red ferricrete quartz. Fine gravel.
SCREEN ANALYSIS (%) PASSING			
75.00mm	100	100	100
63.00	100	100	100
53.00	100	100	100
37.50	100	100	100
26.50	100	100	100
19.00	100	100	100
13.20	100	100	100
4.75	98	97	86
2.00	63	78	65
0.425	44	49	41
0.075	26	29	17
SOIL MORTAR			
Coarse sand 2.00-0.425mm	30	37	36
Coarse fine sand 0.425-0.250mm	8	9	14
Medium fine sand 0.250-0.150mm	7	8	13
Fine sand 0.150-0.075mm	12	9	11
Material <0.075mm	43	37	26
CONSTANTS			
Grading modulus	1,33	1,56	1,23
Liquid limit	24	23	21
Plasticity index	10	8	4
Linear shrinkage (%)	4,5	4	2
Sand equivalent			
Classification - TRB	A-2-4(0)	A-2-4(0)	A-1-b(0)
Classification - TRH14	G7	G7	G6
MOD. AASHTO			
Max dry density (kg/m^3)	2221	2232	2229
OMC (%)	6,4	5,9	6,3
MMC (%)	6,3	5,9	6,4
Dry density (kg/m^3)	2212	2237	2216
% Max dry density	100	100	99
100% Mod CBR	46	50	162
% Swell	0	0	0
NRB			
Dry density (kg/m^3)	2075	2100	2094
% Max dry density	93	94	94
100% NRB CBR	20	23	44
% Swell	0	0	0
PROCTOR			
Dry density (kg/m^3)	1953	2030	2029
% Max dry density	00	91	91
100% Proctor CBR	7	11	32
% Swell	0	0	0
CBR VALUES			
100% Mod AASHTO	49	49	186
98%Mod AASHTO	37	38	116
97%Mod AASHTO	32	33	91
95%Mod AASHTO	25	26	57
93%Mod AASHTO	18	18	40
90%Mod AASHTO	10	9	29

TRH14 of G7 (due primarily to low CBR values) whilst site 3 is classified as a G6 material (due to a low grading modulus).

Road Geometrics

Approximately level road sections are available on haul road 1 at a grade between 0,385% and 0,1%. Grade sections limited in length to about 200m at a grade of 1,7% only.

From this data, three test sites were located to complete critical factor level combinations envisaged in the experimental design (section 3.3). These sites are summarised below and their locations given in Figure 3.9.

SITE 1	CH2560.00-2750.00 (Grade only). Contractor constructed section of haul road 1.
SITE 2	CH1100.00-900.00 (level), CH700.00-900.00 (grade). Mine constructed section of haul road 1.
SITE 3	CH1160.00-1360.00 (level), CH1410.00-1540.00 (grade on curve). Mine constructed section of new haul road 2.

3.3.2.3 New Vaal Colliery

Traffic Volume

New Vaal Colliery produced between 1 100-1 250kt ROM product per month over the analysis period. This may be equated to between 7 857 and 8 928 truck repetitions per month on the most heavily trafficked section of the road (all trucks being converted to R170 equivalents) using an average load factor of between 140t per truck. Coal is sourced from several ramp areas and the possibility exists of examining similar road sections under the action of various laden traffic levels. The unladen traffic volume repetitions cannot easily be determined since discard is transported on an ad-hoc basis back to various points in the pit. The gross vehicle mass (GVM) of an equivalent R170 loaded truck ranges between 257t and 267t and that of an empty truck 102-130t.

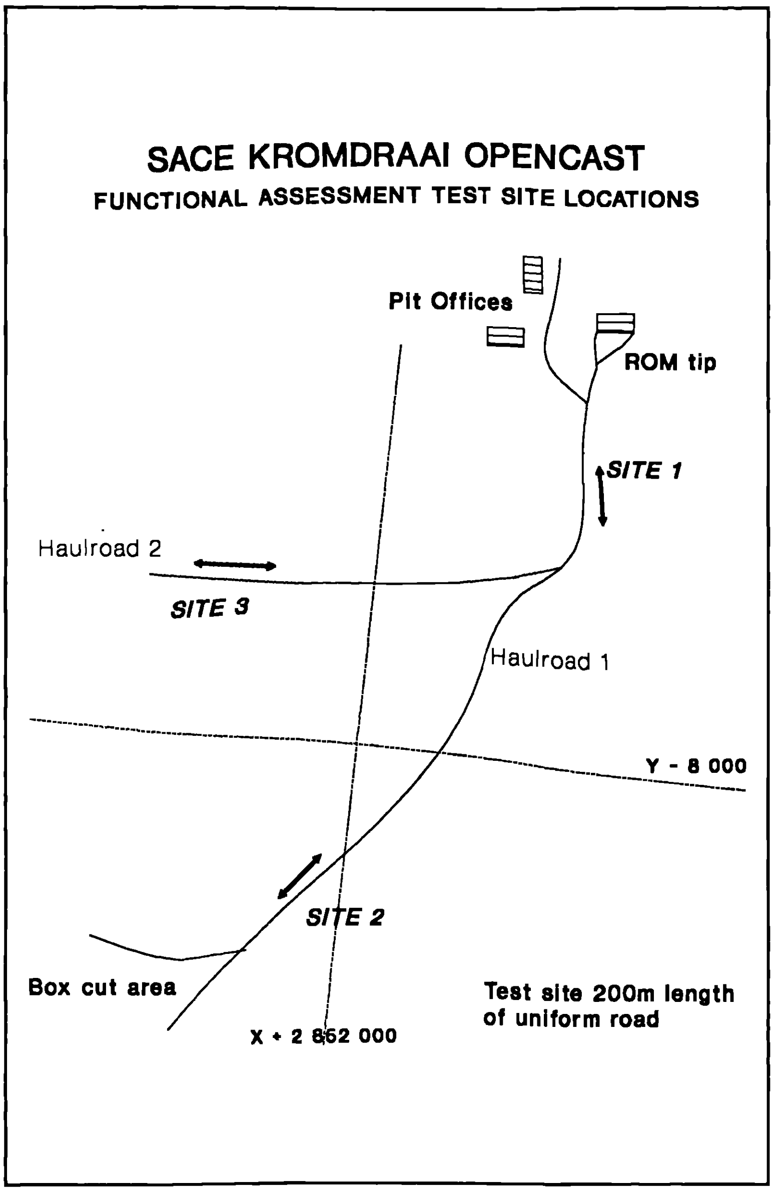

Figure 3.9 Test site locations for functional analysis - Kromdraai Colliery

The mine fleet consists mostly of Euclid R170 (single rear axle with dual wheels) trucks and several Komatsu HD1600 M1 (single rear axle with dual wheels) trucks. In order to make valid comparisons with other test sites, all repetitions were converted to R170 truck equivalents by means of an equivalent load factor. It is assumed that there was negligible difference between the effect of the mine fleet (as operated) and the assumed equivalent fleet of R170 trucks in terms of the effects on haul road functionality.

Wearing Course Material

The wearing course material at New Vaal consists of dolerite (crusher run scalping), soft plinthite and ash in the ratio 40%, 40% and 20%. Table 3.11 gives the results of the laboratory analysis of the wearing course material at New Vaal Colliery test sites. Site 1 was located on the original haul road whilst sites 2 and 3 were located on a more recent construction. This is confirmed from the screen analysis results in which a much larger top size (100% passing 53,00mm) is seen at sites 2 and 3 than at site 1 (100% passing 19,00mm). Site 1 exhibits lower plastic and liquid limit values whilst sites 2 and 3 show higher values. The apparent increase in linear shrinkage with plasticity index (PI) and liquid limit (LL) is not confirmed in this particular mixture, site 3 showing a low linear shrinkage at a PI of 5 and LL of 22. When maximum dry density is also considered it would appear that site 3 may contain considerably more ash and soft plinthite than the other sites.

The bearing strength of the material, in terms of the 7 day soaked CBR at 93%Mod.AASHTO compaction is just below the requirements of a G6 classifiaction (following TRH14) and each material is assigned a G7 classification. The wearing course material at site 3 is the weakest with a maximum CBR of 43 at 100%Mod.AASHTO compaction whilst site 1 exhibits a CBR value of 122 at the same compactive effort.

Road Geometrics

Only approximately level sections are available on the road, varying between horizontal and 0,1% grade. From this data, three test sites were located to complete critical factor level combinations envisaged in the experimental design (section 3.3). These sites are summarised below and their locations given in Figure 3.10.

SITE 1	CH1000.00-12000.00 (level). Main haul road between ramp 1 and 2, carrying maximum traffic volume.
SITE 2	CH1140.00-1380.00 (level). Main haul road diversion, between ramps 3 and 4, carrying intermediate traffic volume.
SITE 3	CH2320.00-2520.00 (level). Main haul road diversion beyond apple cut, approaching ramp 7&8, carrying low traffic volume.

Table 3.11 Laboratory Analysis of Wearing Course Material at New Vaal Colliery

SAMPLE SITE: NEW VAAL COLLIERY	**Site 1**	**Site 2**	**Site 3**
SAMPLE DESCRIPTION	Dolerite, ash, soft plinthite	Dolerite, ash, soft plinthite	Dolerite, ash, soft plinthite
SCREEN ANALYSIS (%) PASSING			
75.00mm	100	100	100
63.00	100	100	100
53.00	100	100	100
37.50	100	98	99
26.50	100	94	98
19.00	100	88	95
13.20	96	83	94
4.75	74	61	77
2.00	58	47	64
0.425	45	32	48
0.075	17	15	19
SOIL MORTAR			
Coarse sand 2.00-0.425mm	21	33	25
Coarse fine sand 0.425-0.250mm	13	13	17
Medium fine sand 0.250-0.150mm	22	12	18
Fine sand 0.150-0.075mm	15	10	11
Material <0.075mm	29	32	29
CONSTANTS			
Grading modulus	1,12	0,94	1,31
Liquid limit	17	24	22
Plasticity index	5	8	5
Linear shrinkage (%)	2.0	4.0	1.5
Sand equivalent			
Classification - TRB	A-1-b(0)	A-2-4(0)	A-1-b(0)
Classification - TRH14	G7	G7	G7
MOD. AASHTO			
Max dry density (kg/m^3)	2242	2006	1721
OMC (%)	5.2	8.7	15.0
MMC (%)	5.3	8.6	14.7
Dry density (kg/m^3)	2218	1984	1745
% Max dry density	99	99	101
100% Mod CBR	94	55	49
% Swell	0.1	0.2	0.1
NRB			
Dry density (kg/m^3)	2079	1896	1669
% Max dry density	93	95	97
100% NRB CBR	21	24	32
% Swell	0.2	0.2	0.0
PROCTOR			
Dry density (kg/m^3)	2023	1799	1628
% Max dry density	90	90	95
100% Proctor CBR	14	15	26
% Swell	0.2	0.1	0.1
CBR VALUES			
100% Mod AASHTO	122	68	43
98%Mod AASHTO	75	46	35
97%Mod AASHTO	59	38	32
95%Mod AASHTO	36	26	27
93%Mod AASHTO	22	21	23
90%Mod AASHTO	13	15	17

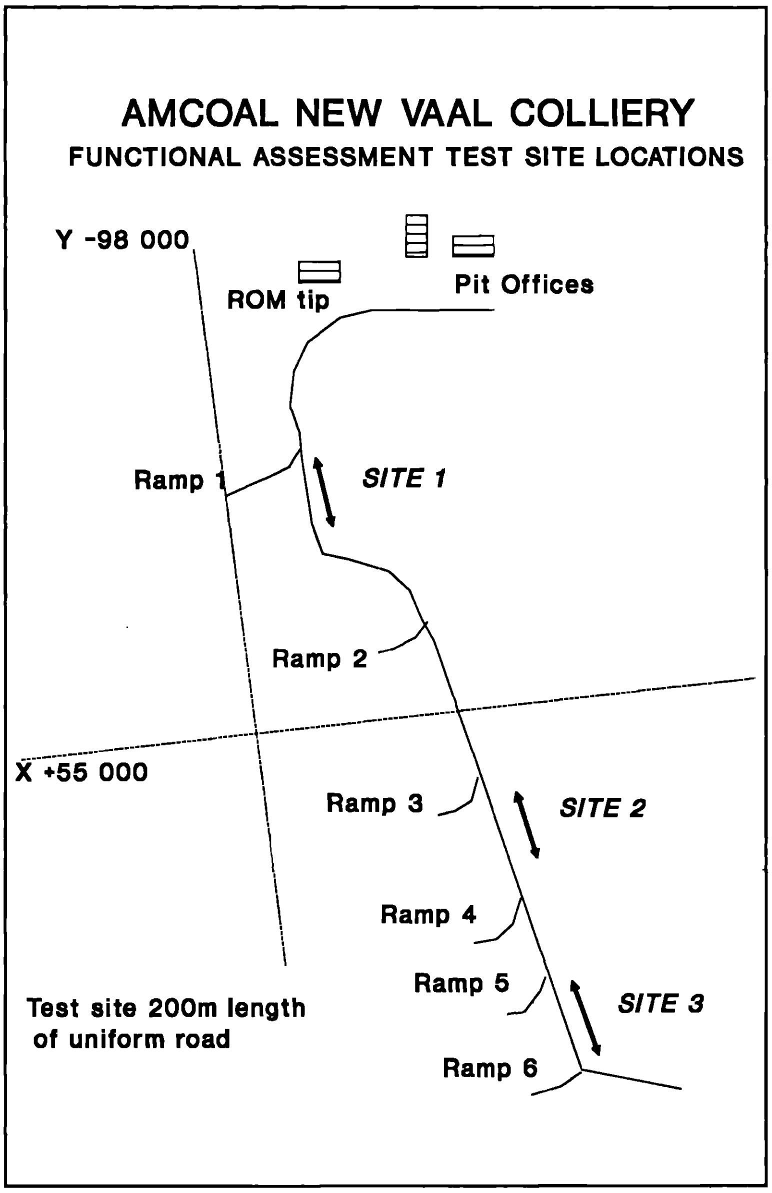

Figure 3.10 Test site locations for functional analysis - New Vaal Colliery.

3.3.2.4 Kleinkopje Colliery

Traffic Volume

Kleinkopje Colliery produced between 550-700kt run-of-mine (ROM) product per month over the analysis period. This may be equated to between 3 286 and 1 078 truck repetitions using an average load factor of between 115t and 127t per truck. Although coal is sourced from four areas, two test sites were chosen which would encompass the greatest variation in traffic volumes. The unladen traffic volume repetitions are similar. The gross vehicle mass (GVM) of the trucks used varies between 271t and 289t for a Euclid R170 (single rear axle with dual wheels) truck and 178-185t for a Euclid CH120/130 (horse single rear dual wheel axle and trailer single dual wheel axle) truck.

The mine operates both R170 and CH120/130 trucks on the 2A haul road and only CH120/130 trucks on the 5W road. In order to make valid comparisons with other test sites, all repetitions were converted to R170 truck equivalents by means of an equivalent load factor. It is assumed that there is negligible difference between the effect of the mine fleet (as operated) and the assumed equivalent fleet of R170 trucks in terms of the effects on haul road functionality.

Wearing Course Material

Local mine ferricrete is used for the construction of the wearing course at Kleinkopje Colliery. Table 3.12 gives the results of the laboratory analysis of the wearing course material at Kleinkopje Colliery test sites. Both materials are similar in terms of grading, site 1 exhibiting a top size of 13,20mm whilst that of site 2 was 4,75mm. A similar proportion of fine material is seen with this ferricrete as at Kriel and Kromdraai Collieries, the grading modulus being below 1,5 in both cases. The Atterberg limits are comparable, showing a PI of 7 and a LL of 23 and 22 for each site.

In terms of bearing strength, both materials are similar, each exhibiting a CBR of 22% and 93%Mod.AASHTO compaction. Accordingly, both materials are classified as a G7 material following TRH14.

Road Geometrics

Approximately level road sections available. Grade sections available between 1,3% (on curve) to 2,6%.

From this data, two test sites were located to complete critical factor level combinations envisaged in the experimental design (section 3.3). These sites are summarised overleaf and their locations given in Figure 3.11.

Table 3.12 Laboratory Analysis of Wearing Course Material at Kleinkopje Colliery

SAMPLE SITE: KLEINKOPJE COLLIERY	**Site 1**	**Site 2**
SAMPLE DESCRIPTION	Pale red ferricrete. Sand.	Pale red ferricrete. Sand.
SCREEN ANALYSIS (%) PASSING		
75.00mm	100	100
63.00	100	100
53.00	100	100
37.50	100	100
26.50	100	100
19.00	100	100
13.20	96	100
4.75	80	84
2.00	64	67
0.425	47	51
0.075	26	23
SOIL MORTAR		
Coarse sand 2.00-0.425mm	27	24
Coarse fine sand 0.425-0.250mm	10	12
Medium fine sand 0.250-0.150mm	10	14
Fine sand 0.150-0.075mm	12	17
Material <0.075mm	41	33
CONSTANTS		
Grading modulus	1,37	1,41
Liquid limit	23	22
Plasticity index	7	7
Linear shrinkage (%)	3,5	3,5
Sand equivalent		
Classification - TRB	A-2-4(0)	A-2-4(0)
Classification - TRH14	G7	G7
MOD. AASHTO		
Max dry density (kg/m^3)	2188	2090
OMC (%)	7,6	8,7
MMC (%)	7,5	8,4
Dry density (kg/m^3)	2197	2118
% Max dry density	100	101
100% Mod CBR	79	79
% Swell	0	0
NRB		
Dry density (kg/m^3)	2112	2011
% Max dry density	97	96
100% NRB CBR	28	31
% Swell	0,1	0
PROCTOR		
Dry density (kg/m^3)	2013	1906
% Max dry density	92	91
100% Proctor CBR	13	8
% Swell	0,1	0,1
CBR VALUES		
100% Mod AASHTO	71	62
98%Mod AASHTO	41	43
97%Mod AASHTO	32	36
95%Mod AASHTO	22	22
93%Mod AASHTO	15	13
90%Mod AASHTO	9	6

SITE 1	CH1930.00-2150.00	5W road (level)
	CH2150.00-2350.00	5W road (grade)
SITE 2	CH540.00-740.00	2A road (level)
	CH200.00-400.00	2A road grade (on curve)

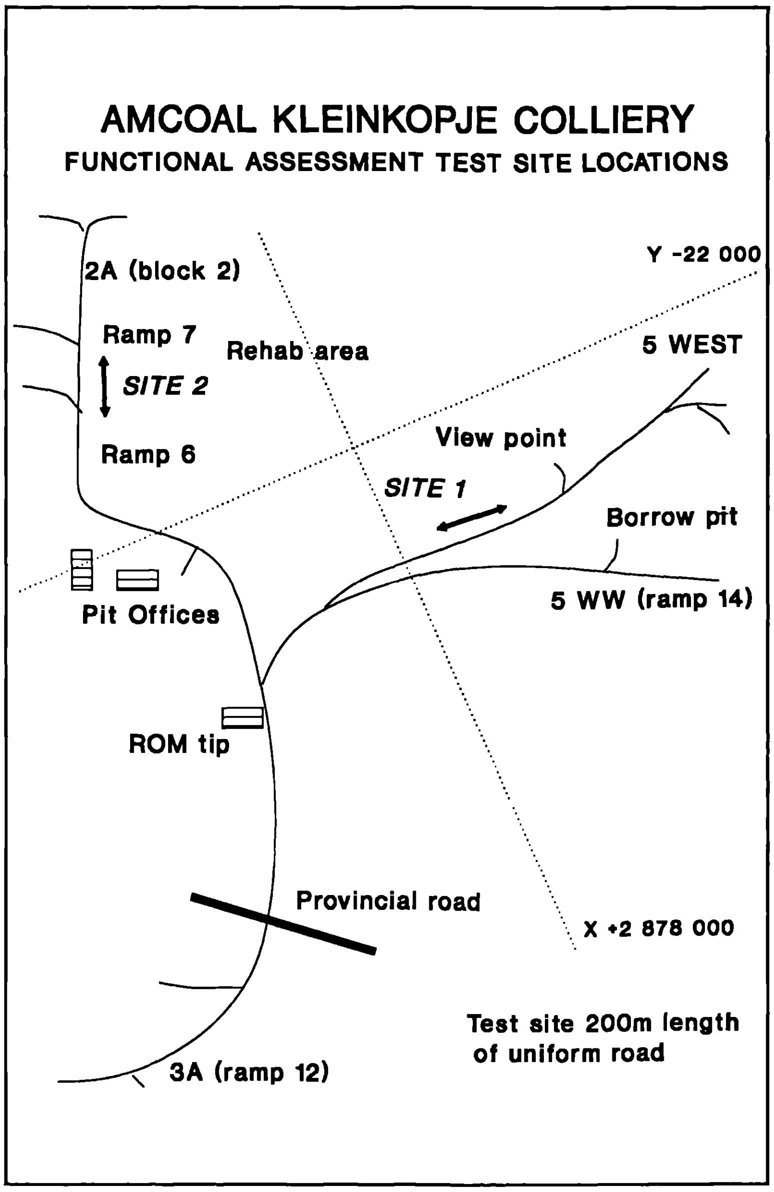

Figure 3.11 Test site locations for functional analysis - Kleinkopje Colliery

Table 3.13 summarises the factor coverage envisaged in the factorial design (section 3.3), the factor levels at each mine site being given. From this it is seen that of the various weathering groups envisaged in the design, only pedocretes and mixtures can be analysed, albeit at both levels of geometry. Whilst this appears to limit the applicability of the results, pedocretes will form the predominant material type for road construction in the Eastern Transvaal coalfield region since the regional distribution of ferricrete (a pedogenic material) is limited by climatic region as defined by Weinert (1980) to where N≤5. As regards the investigation of mixtures, this will lead to the development of guidelines on suitable wearing course material selection by blending of unsuitable or poor quality materials.

Table 3.13 Test Site Location Matrix for Functional Design Research

Wearing Course Material (weathering group)	**Road Geometrics**	
	Level	Grade
Pedocretes	Kriel site 3 Kromdraai site 2 Kromdraai site 3 Kleinkopje site 1 Kleinkopje site 2	Kriel site 3 Kromdraai site 1 Kromdraai site 2 Kromdraai site 3 Kleinkopje site 1 Kleinkopje site 2
Argillaceous		
Arenaceous		
Basic crystalline		
Acid crystalline		
Mixtures	New Vaal site 1 New Vaal site 2 New Vaal site 3 Kriel site 2	Kriel site 1

3.4 Data Collation Requirements for Maintenance Management Research

The maintenance of mine haul roads is an integral component of both the structural and functional designs. However, the management and scheduling of mine haul road maintenance has not been widely reported in the literature, primarily due to the subjective and localised nature of operator experience and required functionality levels. No studies have been reported relating to vehicle operating costs for ultra-heavy vehicles using unpaved mine haul roads. Existing MMS are based on the optimisation of pavement functional performance and vehicle operating and road maintenance costs. By using a similar approach for mine haul road MMS a basic model flowchart can be constructed as shown in Figure 3.12.

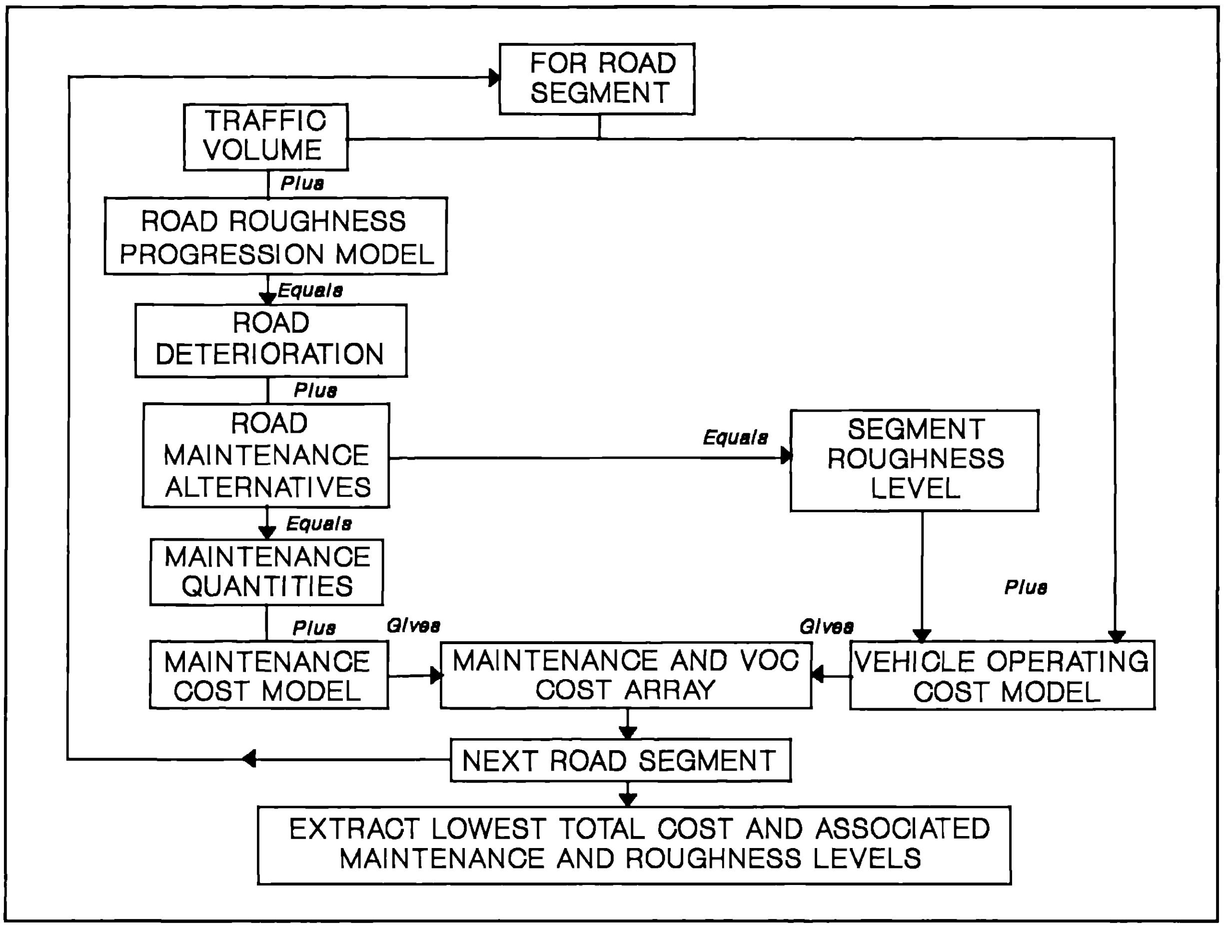

Figure 3.12 Flow Chart of Proposed MMS for Mine Haul Roads (for a single maintenance strategy iteration).

The optimum maintenance strategy commensurate with the minimum total costs can be derived through the combination of models of haul road roughness progression, road maintenance and vehicle operating costs. Each haul road to be assessed can be subdivided into a number of segments in which specific traffic volumes and haul road characteristics are incorporated. The combination of the above-mentioned models and road and traffic characteristics with a variety of road maintenance alternatives for each segement will allow the selection of the lowest total cost alternative for the road, subject to the limitations of the available maintenance equipment and productivities.

The data collation requirements necessary to generate the models presented in Figure 3.12 are summarised in Table 3.14.

Table 3.14 Mine Haul Road MMS Model Data Requirements

MODEL	MODEL COMPONENTS	MODEL DATA REQUIREMENTS
Road roughness progression	Progression models for combined defects comprising road roughness	Subjective evaluation of road roughness defects following 5 point degree and extent classification for; Potholes Corrugations Rutting Loose material Stoniness - fixed Wearing course material properties Evaluation of road roughness to establish correlation with classification from subjective evaluation Coast down tests to establish equivalent rolling resistance and correlation with road roughness.
	Traffic volume	User specified for road segment
	Days since last maintenance	Derived from maintenance strategy
Road maintenance cost	Grader operating cost	Mine cost data for road maintenance fleet and fleet productivities. Mine haul road geometry
	Water car operating cost	
Vehicle operating cost	Fuel cost	Computer-based simulations for representative coal hauling fleet over range of resistances
	Tyre cost	Mine cost data for coal hauling fleet and associated road and vehicle statistics
	Maintenance cost (parts and labour)	

The data collation requirements of the individual models shown in Table 3.14 are discussed in the following sections.

3.4.1 Road Roughness Progression Model

The road roughness progression model is based on the combination of the contributory defects of potholes, corrugations, rutting and loose material. The rate of roughness progression may be determined from consideration of the wearing course material properties, traffic volume and maintenance interval.

A subjective evaluation technique for road roughness was developed in order to facilitate the rapid evaluation of road roughness by mine personnel. This is discussed in more detail in Chapter 13. To enable meaningful comparison of the technique, correlation of the subjective assessment with a quantitively derived road roughness profile generated by use of a high speed profilometer (HSP) was required. For each mine haul road, the subjectively evaluated road roughness for each 100m section can then be correlated with the average HSP roughness over the same sections of road.

The HSP non-contact pavement profiling system consists of a microbus fitted with accelerometers and opto-electronic sensors to capture road roughness profile data. In the case of longitudinal roughness profiling, raw profile data is obtained from height sensors and accelerometers which transmit signals at the rate of 250Hz. The height sensor is an opto-electronic device which beams a collimated ray of light vertically onto the road surface. The position of the illuminated spot is detected and transmitted as a signal proportional to the distance between vehicle and road surface. Rigidly attached to the sensor is a pendulum-type force-balanced accelerometer to monitor vertical accelerations which the height sensor experiences during travel. Numerical integration of these accelerations give a displacement value which is then subtracted from the displacement recorded by the height sensor to produce a longitudinal road profile elevation. Calibration of the HSP profiler took place under laboratory conditions prior to dispatch of the vehicle to the various mine sites.

3.4.2 Road Maintenance Cost Model

The road maintenance cost model is derived from the analysis of mine data covering the cost of maintenance and maintenance fleet productivities. The cost of maintenance per kilometer of road section is subdivided into the following elements:

- Motor grader operating cost (R/km)
- Water truck operating cost (R/km)
- Road maintenance fleet workshop (parts and labour) cost (R/year)

In addition the following operational information was sought with which to define maintenance fleet productivity;

- Number and type of grader in operation
- Number and type of water car in operation
- ROM production tonnages (ie. traffic volumes) for each road segment

Vehicle population data requirements are summarised in Table 3.15. Haul road production and geometric data requirements were collated over the same operating period and incorporated total tons hauled over a section of road, the section length, rise or fall and curvature. A section was defined as a constant tonnage section such that where additional traffic joined the road, a new section was begun.

3.4.3 Vehicle Operating Cost Model

Mine haul truck operating costs consist of fuel, tyre and vehicle maintenance components. The costs of oil and lubrication represent only a small fraction of total vehicle operating costs and are thus disregarded. Depreciation for mine haul trucks is more a function of accounting policy, thus marginal changes in road roughness are unlikely to significantly affect truck life or depreciation policy. Fuel consumption can be determined from commercial vehicle simulation packages which include engine torque/fuel consumption, speed/rimpull and retarder/speed/distance maps. Fuel consumption is related to the rolling resistance of a road and an indication of fuel consumed at constant speeds may be determined from vehicle simulation packages for vehicles comprising a typical coal hauling fleet. Independent

Table 3.15 Vehicle Population Data Collation Requirements

	COAL HAULERS			MAINTENANCE FLEET		
	1	2	3	1	2	3
Vehicle type (make, model)						
Number in use						
Engine type						
Engine power developed (kW@*n* rpm)						
Drive type (electric or mechanical)						
Total fleet hrs travelled since new						
Date of purchase						
Annual operating hours (F94)						
Vehicle replacement price						
Tyres - total number on vehicle						
Tyres - total fitted since new						
Tyres replaced F94						
Tyre size and make						
Tyre replacement cost						

variables which can be used to predict the fuel consumption include vehicle speed, for which simulation can provide basic model data, load, road geometrics and roughness (expressed as rolling resistance). Vehicle operating cost data comprising the components of tyre and maintenance (spares and labour) were collated from mine operating records. Table 3.16 summarises vehicle operating cost data requirements.

Table 3.16 Vehicle Operation Cost Data Requirements

INDIVIDUAL VEHICLE OPERATING COST COMPONENT	UNITS
COAL HAULING OPERATIONS	
Fuel	R/hr or R/year
Tyres	R/hr or R/year
Vehicle maintenance (parts)	R/hr or R/year
Vehicle maintenance (workshop labour). Total workshop hours and average labour hourly cost	R/hr or R/year
ROAD MAINTENANCE OPERATIONS	
Motor grader operating cost	R/t.km or R/year
Water truck operating cost	R/t.km or R/year
Actual or estimated grader productivity	km graded/h
Actual or estimated water-car productivity	km watered/h

3.5 Summary of Experimental Designs

3.5.1 Structural Design Research

The experimental design adopted for haul road structural design research was based on the identification of applied load, subgrade strength and structural thickness and layer strengths as the independent variables (factors). The approach adopted involved the quantification of these factors for existing haul roads to determine the efficacy of the various design options. To fully characterise the structural performance of existing or future designs of haul roads, each factor should be analysed at various levels. A designed factorial experiment was used in which these factors, together with their levels of analysis were incorporated in the sample matrix for the structural design research. From an analysis of the available mine sites it was found that all combinations of factors and levels could be accommodated in the proposed experimental design matrix.

Test site locations envisaged in the experimental matrix were located on a mine's haul road.

An indication of the bearing capacity of the subgrade in that location was obtained with the dynamic cone penetrometer (DCP) at the point where the multi-depth deflectometer (MDD) was to be installed. Structural thickness data was obtained from historical road design data, corroborated with DCP data for individual pavement layer thickness assessment and depth of transducer installation.

For each of the independent variables actual field values are recorded and in addition, the dependent variables of resilient deformations (in each pavement layer and in the subgrade) and permanent deformation (after a number of load repetitions) are also be measured. Load application was achieved through the use of mine haul trucks and actual wheel loads were measured directly or by recourse to tyre test data.

3.5.2 Functional Design Research

A designed factorial experiment was recognised as the most efficient approach in analysing the independent variables (factors) at specific levels. The wearing course material, road geometrics and climate were considered to be the major independent variables affecting the performance of unpaved roads. Levels included consideration of road longitudinal profile an incorporated level and grade sections. Factor levels considered for material type were based on weathering products encountered in the coal producing regions of South Africa and included pedocretes, argillaceous, arenaceous, basic crystalline and acid crystalline, together with mixtures of these. The choice of levels for the independent variable of climate was based on Weinert's N-value. This choice is advantageous since the weathering products used as levels for the independent variable of wearing course material are unique for the particular N-value contour chosen and that the N-value numbers are distinct physiographical boundaries. Since most Transvaal strip coal mines are situated within the physiographical region where N=2 to N=5, this effectively discounts climate as an independent variable in the analysis.

From an analysis of the available mine sites it was found that only pedocretes and mixtures of material were available and thus, although generating usefull data directly applicable to most Transvaal strip-coal mines, the experimental design was only partly satisfied.

A number of additional dependent variables were also recognised for each test section envisaged in the sample matrix and included days since last maintenance, traffic (t/day), moisture conditions of surface layer, surface erosion and surface drainage. Laboratory tests to determine the correlation with, or modification to existing wearing course material selection guidelines involved the quantitative analysis of grading, Atterberg limits and linear shrinkage, California Bearing Ratio (CBR) and classification according to TRH14.

A visual evaluation was used for the qualitative determination of surface moisture conditions, roadside and on-road drainage and erosion (longitudinal and cross directions) over a full climatic cycle. The variables affecting haul road functional performance were derived from consideration of the properties of the wearing course surface (material type), those related to the road formation and those related to the way the road user experiences the road. A number of key functional defects were recognised and proposed as a basis for evaluating haul road functionality and to ascertain the validity and applicability of published selection guidelines.

3.5.3 Maintenance Management Research

The maintenance of mine haul roads is an integral component of both the structural and functional designs. However, the management and scheduling of mine haul road maintenance has not been widely reported in the literature, primarily due to the subjective and localised nature of operator experience and required functionality levels. It was proposed that the structure of existing MMS be adopted to generate a basic MMS for mine haul roads.

The MMS model for mine haul roads required the assessment and modelling of haul road roughness progression, road maintenance and vehicle operating costs. For each of these models, specific data needs were described in terms of model components and their associated field data and evaluation requirements. Available mine data was found not to be in a form suitable for direct inclusion in the proposed models and additional data requirements were tabulated to complete the mine haul road MMS. By combining the above-mentioned models and road and traffic characteristics with a variety of road maintenance alternatives, the selection of the lowest total cost alternative for the road, subject to the limitations of the available maintenance equipment and productivities, can be made.